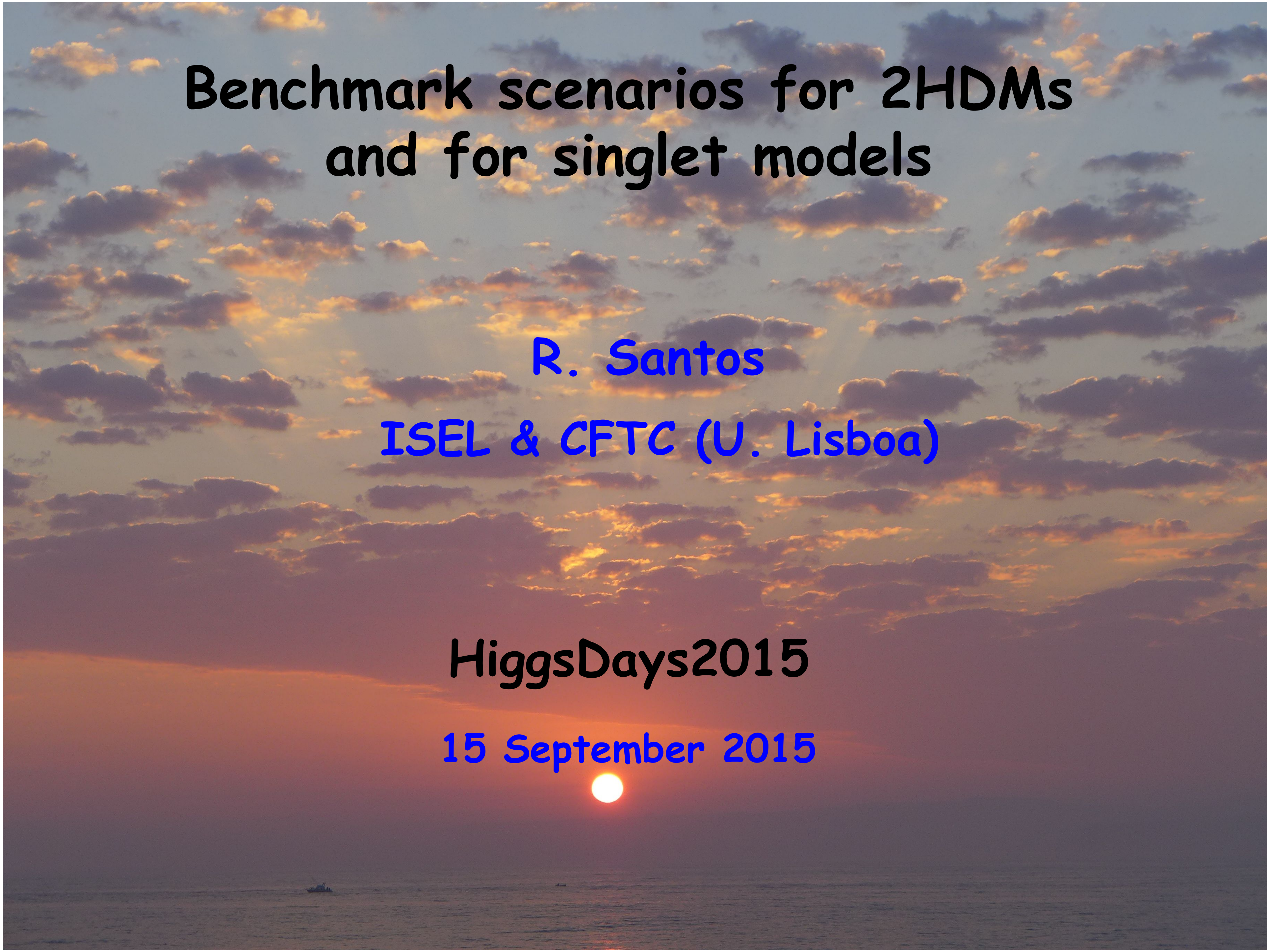


Benchmark scenarios for 2HDMs and for singlet models

R. Santos

ISEL & CFTC (U. Lisboa)

HiggsDays2015

15 September 2015

1st call - CP-conserving 2HDM

Meeting 23 June 2015

BP1: *Howard Haber, Oscar Stål*
Phenomenological benchmarks for the CP-conserving 2HDM with softly-broken Z_2-symmetry.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/HH_OS_2HDM_Benchmarks.pdf

BP2: *Felix Kling, Shufang Su*
Benchmark points for exotic Higgs decays.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/Exotic_Benchmarks.pdf

BP3: *Glauber Dorsch, Stephan Huber, Ken Mimasu, Jose Miguel No*
We attach our 2HDM benchmarks for LHC searches, based on our recent work 1405.5537, together with some discussion on their salient features and motivation.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_Cosmic_Benchmarks.pdf

BP4: *Robin Aggleton, Daniele Barducci, Alexandre Nikitenko, Stefano Moretti, Claire Shepherd-Themistocleous*
Here in attach a brief note explaining the benchmark scenarios we chose (.pdf and .tex), together with a file with the definition of the benchmarks in terms of 2HDM parameter. We are still working on other benchmark scenarios mentioned in a previous mail (higgs-to-2-Higgs topologies) and we will provide them shortly.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_WG-final.pdf

BP5: *Agnieszka Ilnicka, Maria Krawczyk, Tania Robens*
Please find attached a short writeup containing benchmarks for the IDM. This note should be seen as a preview of a full publication which should then be used as a reference.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/IDM_benchmarks.pdf

BP6: *David Lopez-Val*
Following your call for 2HDM benchmark suggestions, I'd like to contribute with one of the scenarios we devised for our Higgs pair study [arXiv:1407.0281]. Please find attached all the details, hopefully complying with the indications given in your email.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/fermiophobic.pdf

The softly broken Z_2 symmetric 2HDM has no tree-level FCNCs. We further assume a CP-conserving potential

$$\boxed{\begin{aligned} V(\Phi_1,\,\Phi_2) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\ & + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right] \end{aligned}}$$

- m^2_{12} and λ_5 real and the vacuum configuration is (CP-conserving)

$$\boxed{\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}}$$

and the common convention for the ratio of the vacuum expectation values is

$$\tan\beta = \frac{v_2}{v_1} \qquad \text{with} \qquad 0 \le \beta \le \frac{\pi}{2}$$

The model has three neutral states and two charged states:

- **Two CP-even states h and H with $m_h < m_H$.**
- **One CP-odd state A.**
- **Two charged states $H^{\pm}$.**

The matrix that diagonalises the CP-even states mass matrix

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

and the common convention for the range of α is

$$-\frac{\pi}{2} \le \alpha \le \frac{\pi}{2}$$

Higgs couplings to gauge bosons

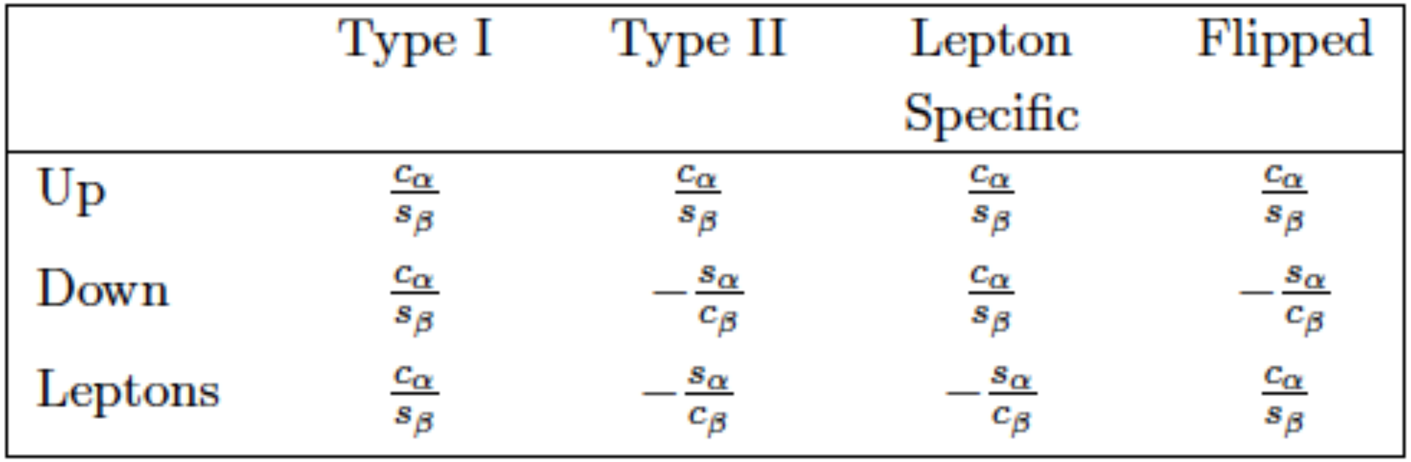
$$g_{2HDM}^{hVV} = \sin(\beta-\alpha)\; g_{SM}^{hVV} \qquad V = W, Z$$

$$g_{2HDM}^{HVV} = \cos(\beta-\alpha)\; g_{SM}^{hVV} \qquad V = W, Z$$

Yukawa couplings

Φ_2 always couples to up-type quarks

Type I	Φ_2 to leptons and to down-type quarks
Type II	Φ_1 to leptons and to down-type quarks
Type F=X=III	Φ_2 to leptons Φ_1 to down-type quarks
Type LS=Y=IV	Φ_1 to leptons Φ_2 to down-type quarks



	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
Down	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$
Leptons	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$

Lightest
Higgs couplings

The Higgs basis* of the Z_2 symmetric 2HDM

The Higgs basis doublets are defined relative to Z_2 basis doublets as

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

and the potential can be written as

$$\begin{aligned} V(\Phi_1,\ \Phi_2) = {} & Y_1 H_1^{+} H_1 + Y_2 H_2^{+} H_2 + \left(Y_3 H_1^{+} H_2 + \text{h.c.}\right) + \frac{Z_1}{2}\left(H_1^{+} H_1\right)^2 + \frac{Z_2}{2}\left(H_2^{+} H_2\right)^2 \\ & + Z_3\left(H_1^{+} H_1\right)\left(H_2^{+} H_2\right) + Z_4\left(H_1^{+} H_2\right)\left(H_2^{+} H_1\right) \\ & + \left\{\frac{Z_5}{2}\left(H_1^{+} H_2\right)^2 + \left[Z_6\left(H_1^{+} H_1\right) + Z_7\left(H_2^{+} H_2\right)\right] H_1^{+} H_2 + \text{h.c.}\right\} \end{aligned}$$

$$\langle H_1 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix};\quad \langle H_2 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad v^2 = v_1^2 + v_2^2$$

* no relation with "Higgs basis" in EFT

$$M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

$$\kappa_i = \frac{g_{2HDM}}{g_{SM}}$$

at tree-level

$$\kappa_i^2 = \frac{\Gamma^{2HDM}(h \to i)}{\Gamma^{SM}(h \to i)}$$

- **Alignment limit (aka SM-like limit)**

$$\sin(\beta-\alpha) = 1 \quad \Rightarrow \quad \kappa_F = 1; \quad \kappa_V = 1$$

- **Decoupling limit**

$$\sin(\beta-\alpha) = 1 \quad \Rightarrow \quad m_\Phi^2 = M^2 + \sum_i \lambda_i v^2 + O\left(\frac{v^4}{M^2}\right) \quad (\text{with } \Phi = H, A, H^\pm)$$

Setting $M^2 >> \lambda_i v^2$

Gunion, Haber (2003).

Kanemura, Okada, Senaha, Yuan (2004).

Ginzburg, Krawczyk (2005).

all heavy scalars masses are determined
by M and independent of the λ

$$M^2 \approx m_H^2 \approx m_A^2 \approx m_{H^\pm}^2 >> \lambda_i v^2$$

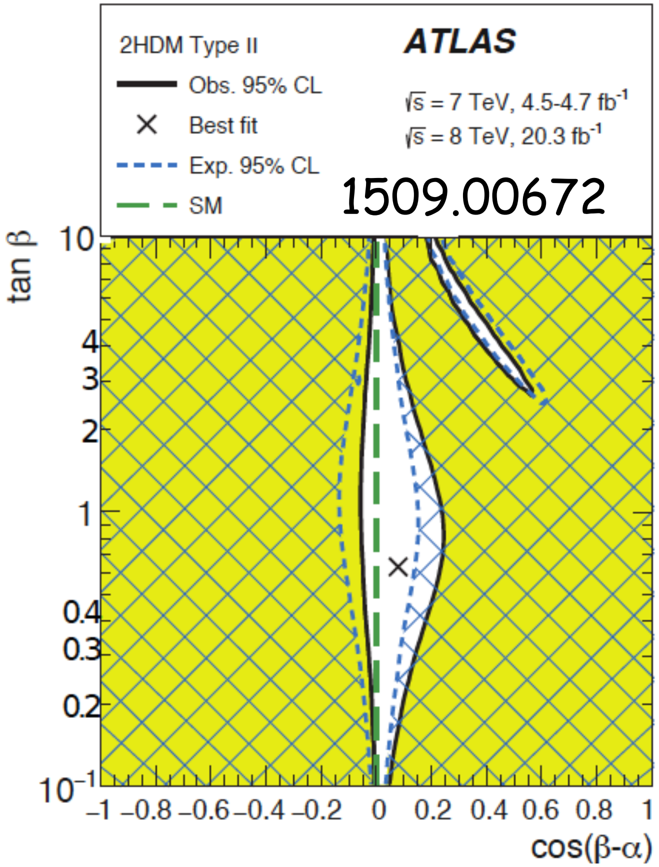
- **Wrong-sign limit (type II and F)**

FERREIRA, GUNION, HABER, RS (2014).

FERREIRA, GUEDES, SAMPAIO, RS (2014).

$$\sin(\beta+\alpha)=1 \quad \Rightarrow \quad \kappa_D = -1 \quad (\kappa_U = 1)$$

$$\sin(\beta-\alpha)=\frac{\tan^2\beta-1}{\tan^2\beta+1} \quad \Rightarrow \quad \kappa_V \geq 0 \ \text{ if } \ \tan\beta \geq 1 \qquad \kappa_D\kappa_V<0$$



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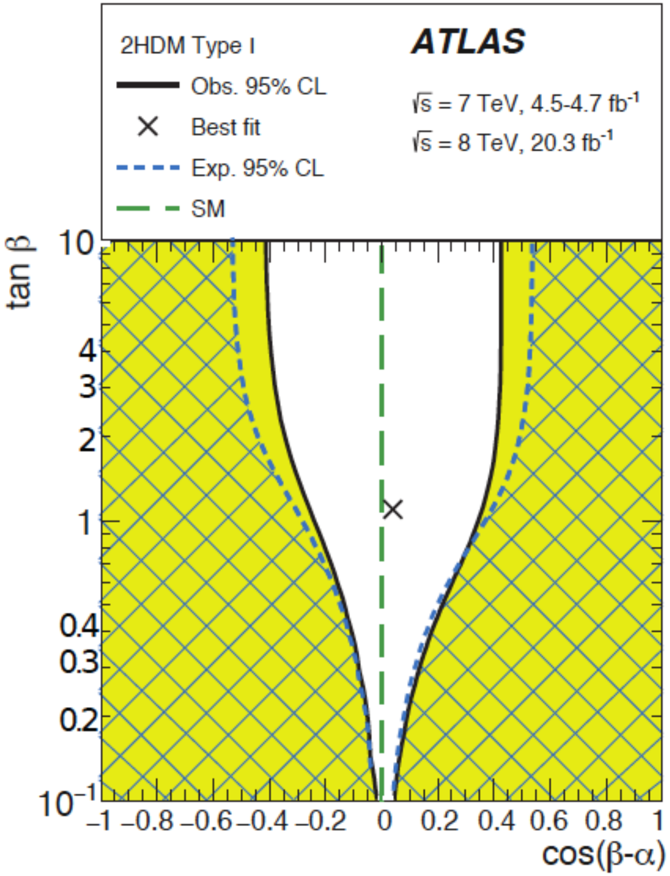


- **Type I**

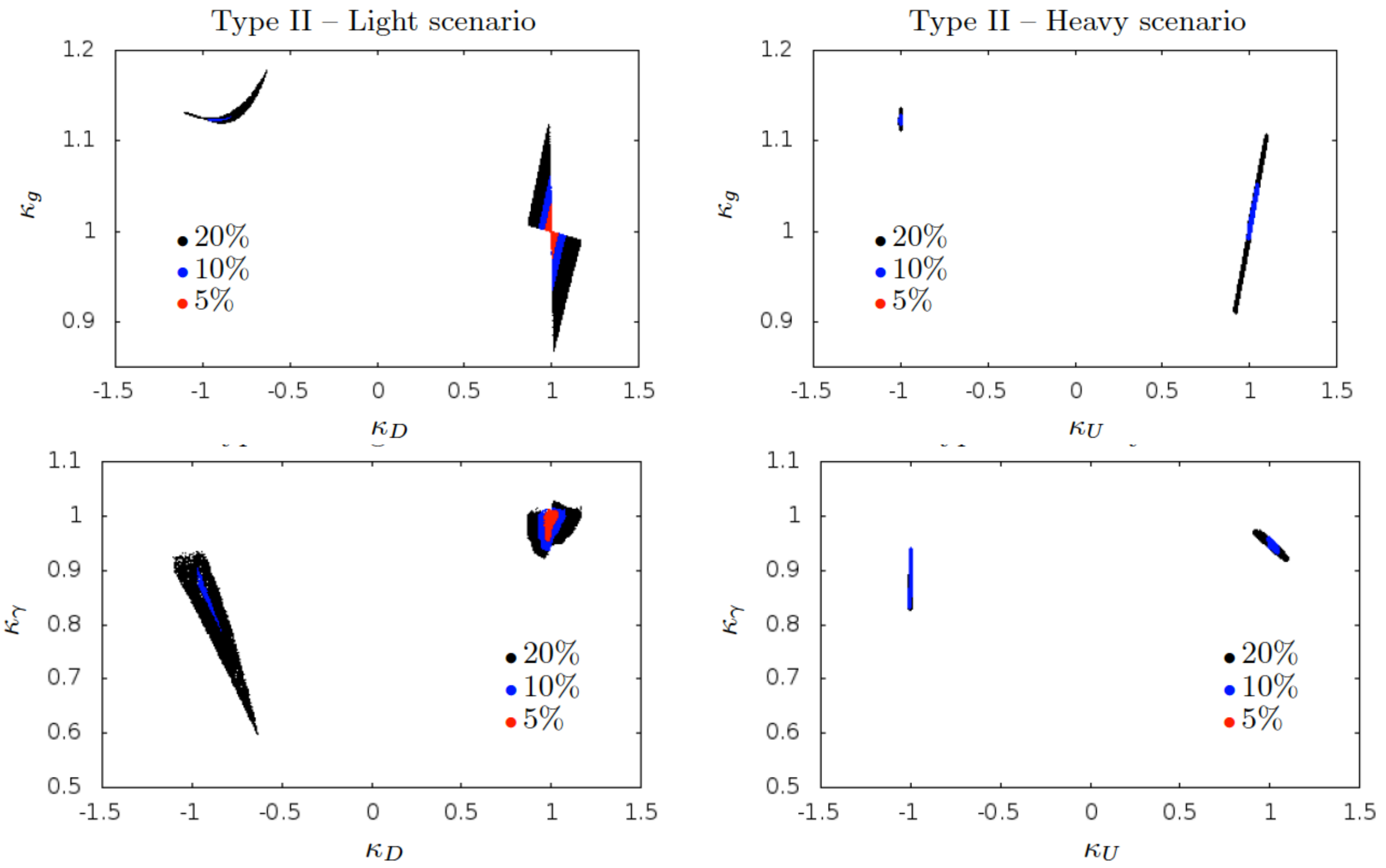
$$\sin(\beta+\alpha)=1 \quad \Rightarrow$$

$$\kappa_U = \kappa_D = \kappa_L = 1$$

still

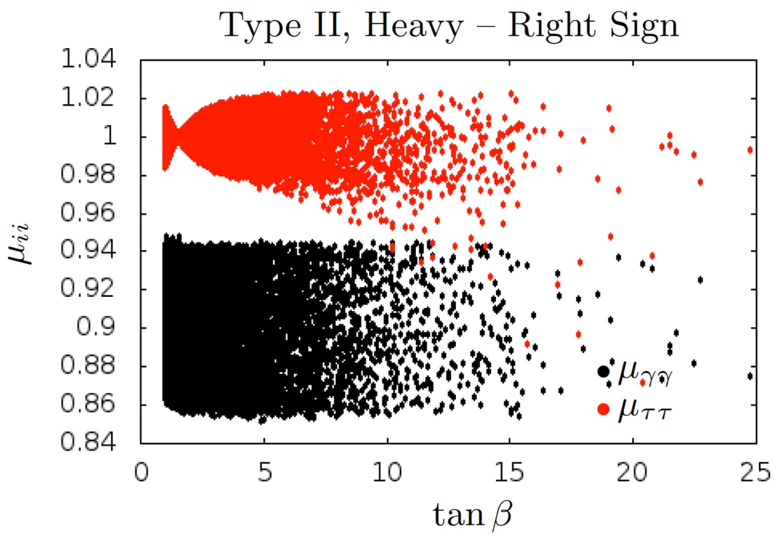
$$\sin(\beta-\alpha)=\frac{\tan^2\beta-1}{\tan^2\beta+1}$$

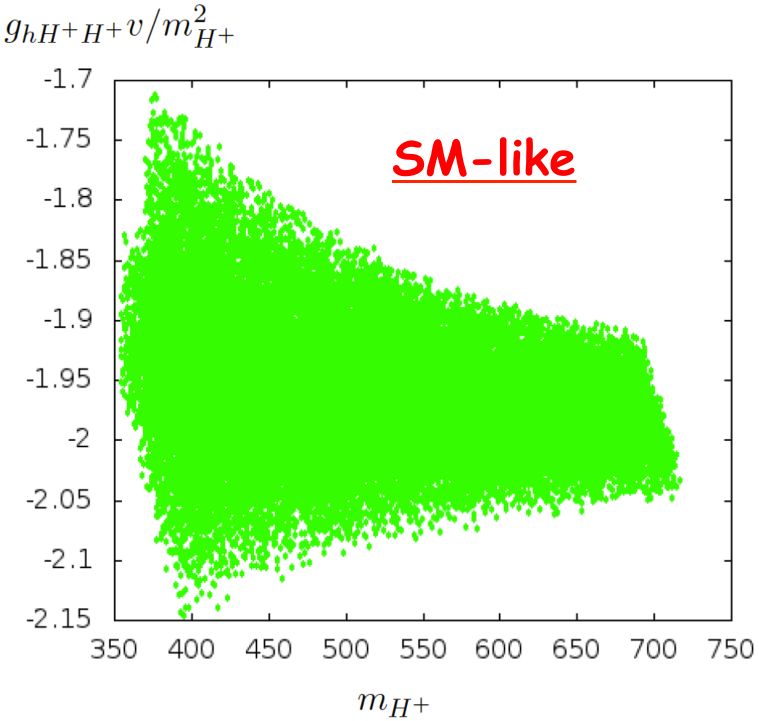
- **Non-decoupling and SM-like heavy Higgs**



5% would exclude the wrong sign in both scenarios but also the heavy scenario in the SM-like limit due to the effect of charged Higgs loops + theoretical and experimental constraints.

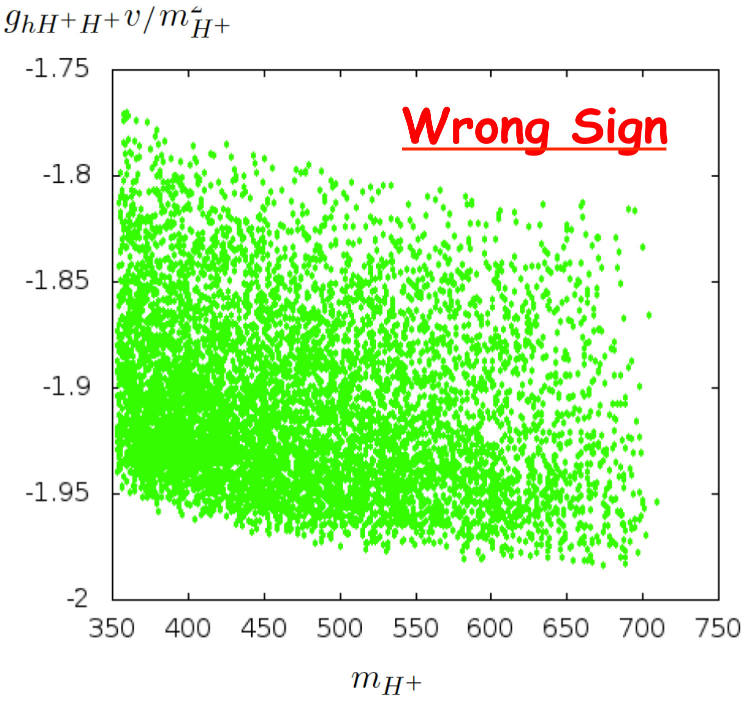
- **Non-decoupling and SM-like heavy Higgs**





$$g^{SM-like}_{HH^+H^-} \approx -\frac{2m^2_{H^\pm} - m^2_H - 2M^2}{v^2}$$

$$g^{Wrong\ Sign}_{HH^+H^-} \approx -\frac{2m^2_{H^\pm} - m^2_H}{v^2}$$



Boundness from below

$$M < \sqrt{m^2_H + m^2_h/\tan^2\beta}$$

b -> s γ

$$m^2_{H^\pm} > \ 340\ \ \text{GeV}\ (\sim 500\ \text{GeV})$$

UPDATED IN MISIAK EAL (2015).

Free parameters

Parameter	Z_2 basis	Hybrid basis
Masses	m_h, m_H, m_A, $m_{H^\pm}$	m_h, m_H
Angles	$\tan\beta$, $(\beta-\alpha)$	$\tan\beta$, $(\beta-\alpha)$
Other	$m_{12}{}^2$	Z_4, Z_5, Z_7

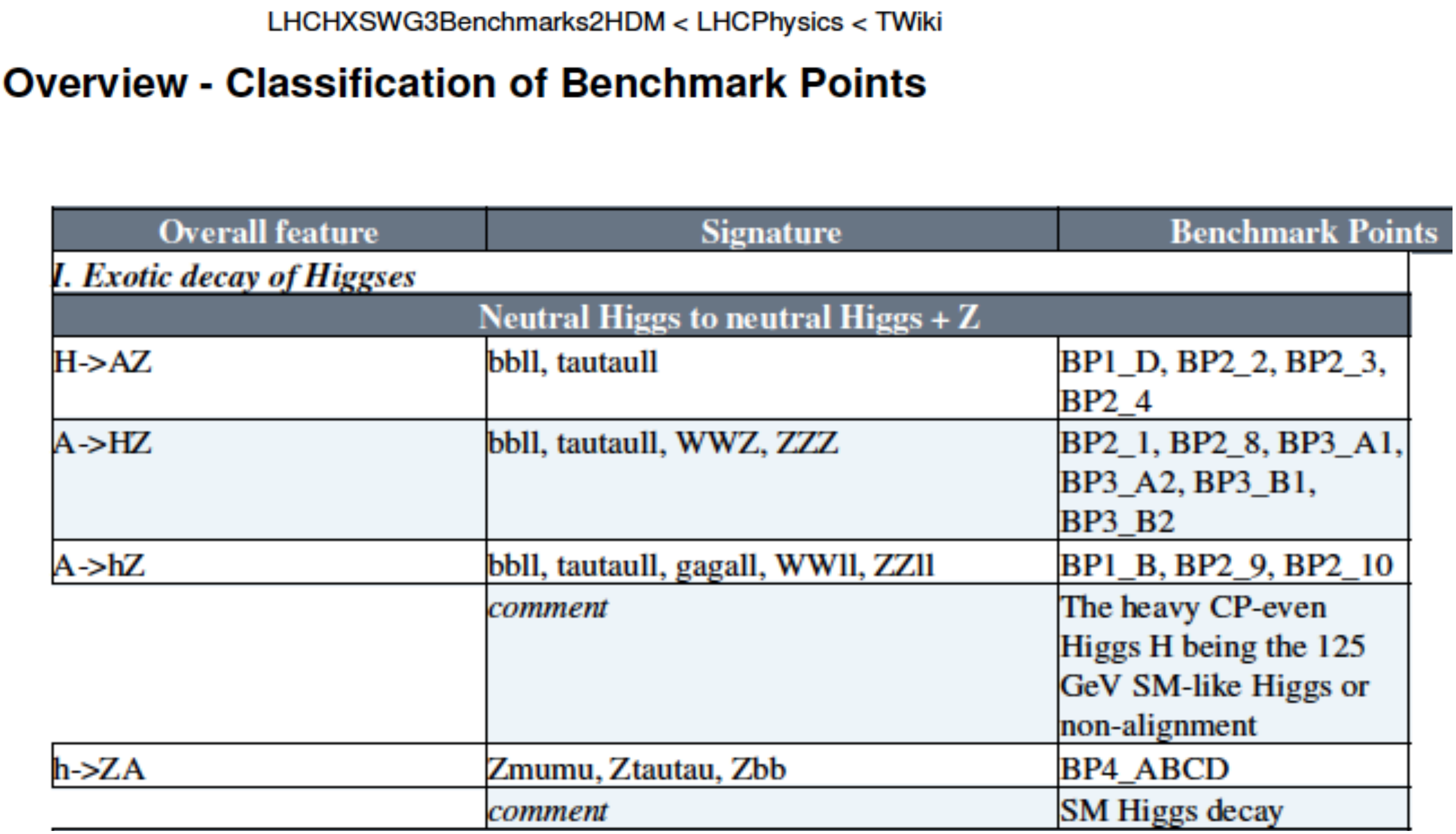
$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2\,,$$

$$Z_2 \equiv \lambda_1 s_\beta^4 + \lambda_2 c_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2\,,$$

$$Z_i \equiv \tfrac{1}{4}s_{2\beta}^2\big[\lambda_1 + \lambda_2 - 2\lambda_{345}\big] + \lambda_i\,, \quad (\text{for } i = 3, 4 \text{ or } 5)\,,$$

$$Z_6 \equiv -\tfrac{1}{2}s_{2\beta}\big[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta}\big]\,,$$

$$Z_7 \equiv -\tfrac{1}{2}s_{2\beta}\big[\lambda_1 s_\beta^2 - \lambda_2 c_\beta^2 + \lambda_{345} c_{2\beta}\big]\,,$$



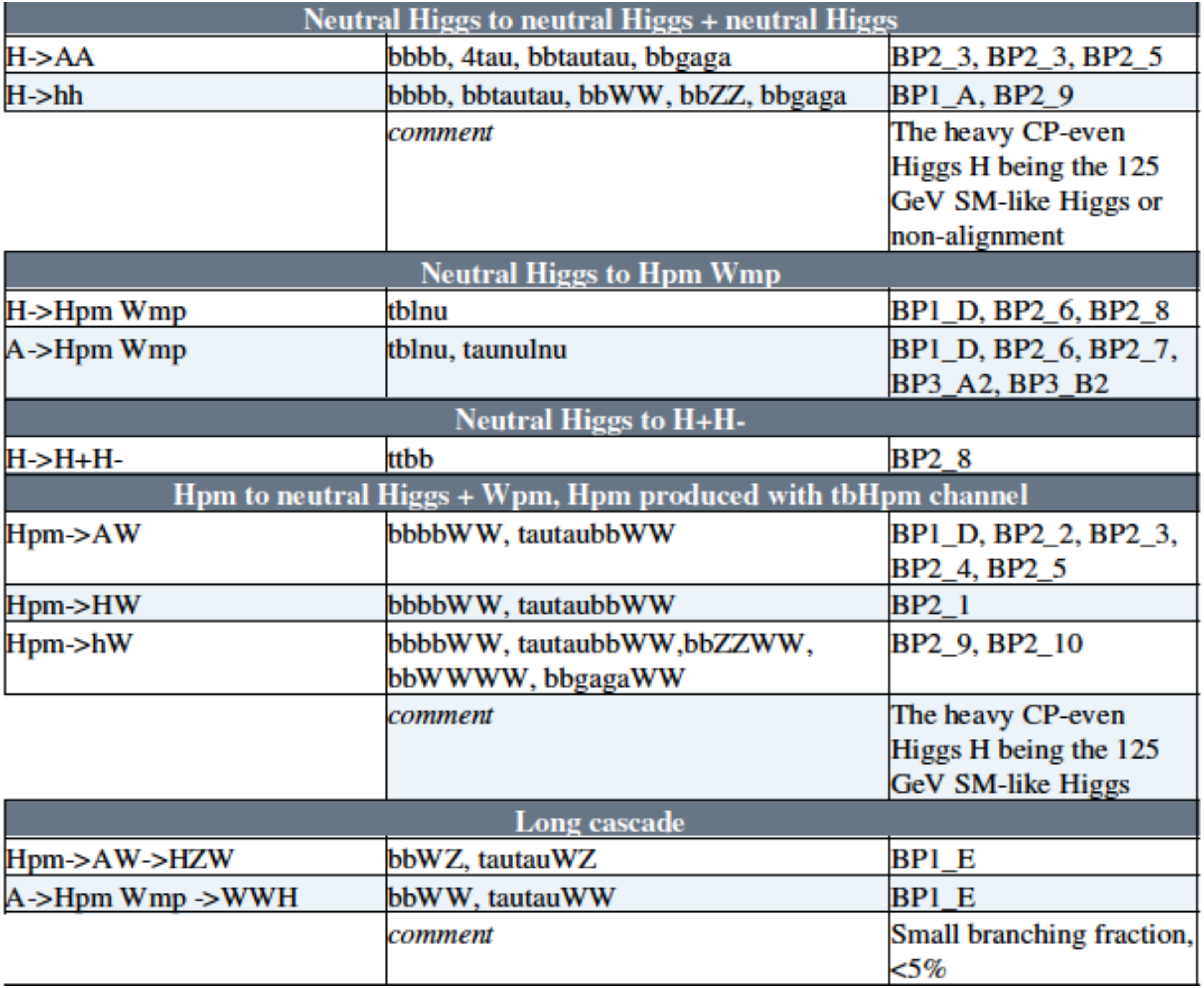
LHCHXSWG3Benchmarks2HDM < LHCPhysics < TWiki

Overview - Classification of Benchmark Points

Overall feature	Signature	Benchmark Points
I. Exotic decay of Higgses		
Neutral Higgs to neutral Higgs + Z		
H->AZ	bbll, tautaull	BP1_D, BP2_2, BP2_3, BP2_4
A->HZ	bbll, tautaull, WWZ, ZZZ	BP2_1, BP2_8, BP3_A1, BP3_A2, BP3_B1, BP3_B2
A->hZ	bbll, tautaull, gagall, WWll, ZZll	BP1_B, BP2_9, BP2_10
	comment	The heavy CP-even Higgs H being the 125 GeV SM-like Higgs or non-alignment
h->ZA	Zmumu, Ztautau, Zbb	BP4_ABCD
	comment	SM Higgs decay

The benchmarks are discussed in detail in

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Benchmarks2HDM



<table>
<tr><th colspan="3">Neutral Higgs to neutral Higgs + neutral Higgs</th></tr>
<tr><td>H->AA</td><td>bbbb, 4tau, bbtautau, bbgaga</td><td>BP2_3, BP2_3, BP2_5</td></tr>
<tr><td>H->hh</td><td>bbbb, bbtautau, bbWW, bbZZ, bbgaga</td><td>BP1_A, BP2_9</td></tr>
<tr><td></td><td><i>comment</i></td><td>The heavy CP-even Higgs H being the 125 GeV SM-like Higgs or non-alignment</td></tr>
<tr><th colspan="3">Neutral Higgs to Hpm Wmp</th></tr>
<tr><td>H->Hpm Wmp</td><td>tblnu</td><td>BP1_D, BP2_6, BP2_8</td></tr>
<tr><td>A->Hpm Wmp</td><td>tblnu, taunulnu</td><td>BP1_D, BP2_6, BP2_7, BP3_A2, BP3_B2</td></tr>
<tr><th colspan="3">Neutral Higgs to H+H-</th></tr>
<tr><td>H->H+H-</td><td>ttbb</td><td>BP2_8</td></tr>
<tr><th colspan="3">Hpm to neutral Higgs + Wpm, Hpm produced with tbHpm channel</th></tr>
<tr><td>Hpm->AW</td><td>bbbbWW, tautaubbWW</td><td>BP1_D, BP2_2, BP2_3, BP2_4, BP2_5</td></tr>
<tr><td>Hpm->HW</td><td>bbbbWW, tautaubbWW</td><td>BP2_1</td></tr>
<tr><td>Hpm->hW</td><td>bbbbWW, tautaubbWW,bbZZWW, bbWWWW, bbgagaWW</td><td>BP2_9, BP2_10</td></tr>
<tr><td></td><td><i>comment</i></td><td>The heavy CP-even Higgs H being the 125 GeV SM-like Higgs</td></tr>
<tr><th colspan="3">Long cascade</th></tr>
<tr><td>Hpm->AW->HZW</td><td>bbWZ, tautauWZ</td><td>BP1_E</td></tr>
<tr><td>A->Hpm Wmp ->WWH</td><td>bbWW, tautauWW</td><td>BP1_E</td></tr>
<tr><td></td><td><i>comment</i></td><td>Small branching fraction, <5%</td></tr>
</table>

The benchmarks are discussed in detail in

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Benchmarks2HDM

Which planes to choose?

Scalar to two gauge bosons

$$H \to W^+W^-(ZZ) \qquad \text{plane: } (m_H,\ \cos(\beta-\alpha))$$

Scalar to one scalar and one gauge boson (m_h = 125 GeV)

$$H \to AZ;\ \underline{A \to HZ} \qquad \text{plane: } (m_H,\ m_A);\ (m_{H(A)},\ \cos(\beta-\alpha))$$

Baryogenesis $\quad m_A - m_H \approx v$ and light m_H $\quad$ large Br(A → HZ)

$$A \to hZ \qquad \text{plane: } (m_A,\ \cos(\beta-\alpha))$$

Which planes to choose?

SM-like Higgs decay to one scalar and one gauge boson (m_h = 125 GeV)

$$h \rightarrow (A \rightarrow \mu^+\mu^- / \tau^+\tau^- / b\bar{b})\, Z \;\; \text{plane:} \;\; (m_A, \tan\beta);\; (m_A,\; \cos(\beta - \alpha))$$

light m_A = 6 to 70 GeV

Scalar to two scalar decays (m_h = 125 GeV)

$$H \rightarrow hh;\; H \rightarrow AA \qquad \text{plane:} \;\; (m_H, \tan\beta \text{ or } \cos(\beta - \alpha));(m_H, m_A)$$

$$\mathrm{h} \rightarrow AA \qquad \text{plane:} \;\; (m_A, \tan\beta \text{ or } \cos(\beta - \alpha))$$

Which planes to choose?

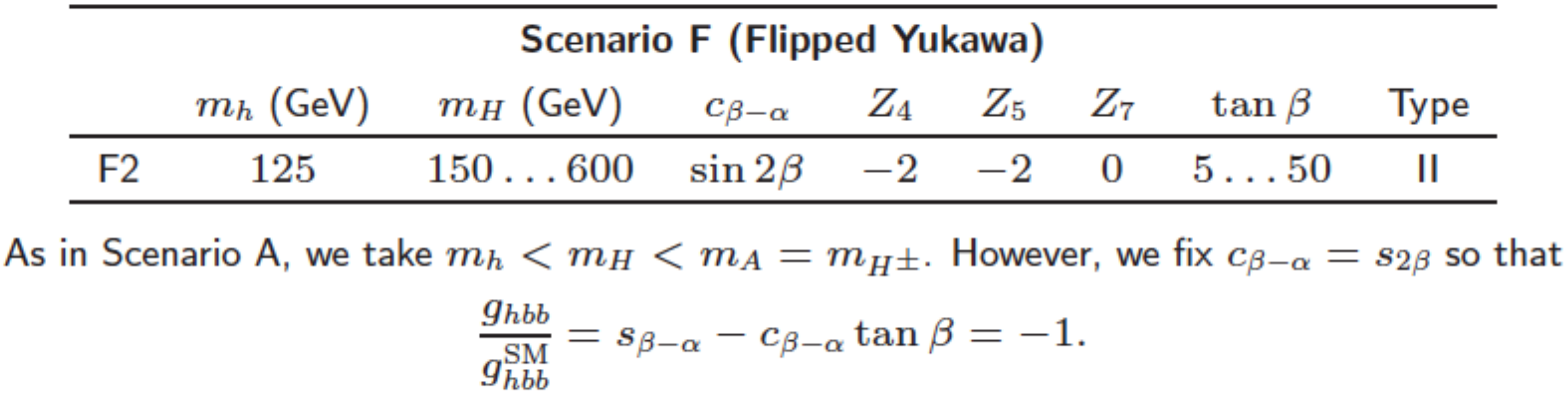
Long Cascade

$$pp \to A \to H^{\pm}W^{\mp} \to HW^{\pm}W^{\mp} \to (H \to)W^{\pm}W^{\mp}$$

$$\text{plane: } (m_A,\ m_H);\ (m_A,\ \cos(\beta-\alpha));\ (m_A,\ \tan\beta)$$

Scenarios vs. Benchmarks?

The wrong sign scenario



Scenario F (Flipped Yukawa)

	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
F2	125	$150\ldots600$	$\sin 2\beta$	-2	-2	0	$5\ldots50$	II

As in Scenario A, we take $m_h < m_H < m_A = m_{H^\pm}$. However, we fix $c_{\beta-\alpha} = s_{2\beta}$ so that

$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta = -1 .$$

The Inert 2HDM

$$V(\Phi_1,\ \Phi_2)/.\, m_{12}^2 \ \rightarrow 0 \qquad \langle \Phi_1 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix};\ \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad \begin{cases} \Phi_1 \rightarrow \Phi_S \\ \Phi_2 \rightarrow \Phi_D \end{cases}$$

The first doublet contains the SM-like Higgs boson h, and the second doublet contains four dark (inert) scalars H, A and H±.

H is taken to be the lightest scalar (stable).

Free parameters (Inert)

Parameter	2HDM (Z_2 basis)	Inert (Z_2 basis)
Masses	m_h, m_H, m_A, $m_{H\pm}$	m_h, m_H, m_A, $m_{H\pm}$
Angles	$\tan\beta$, $(\beta-\alpha)$	
Other	$m_{12}{}^2$	λ_2, λ_{345}

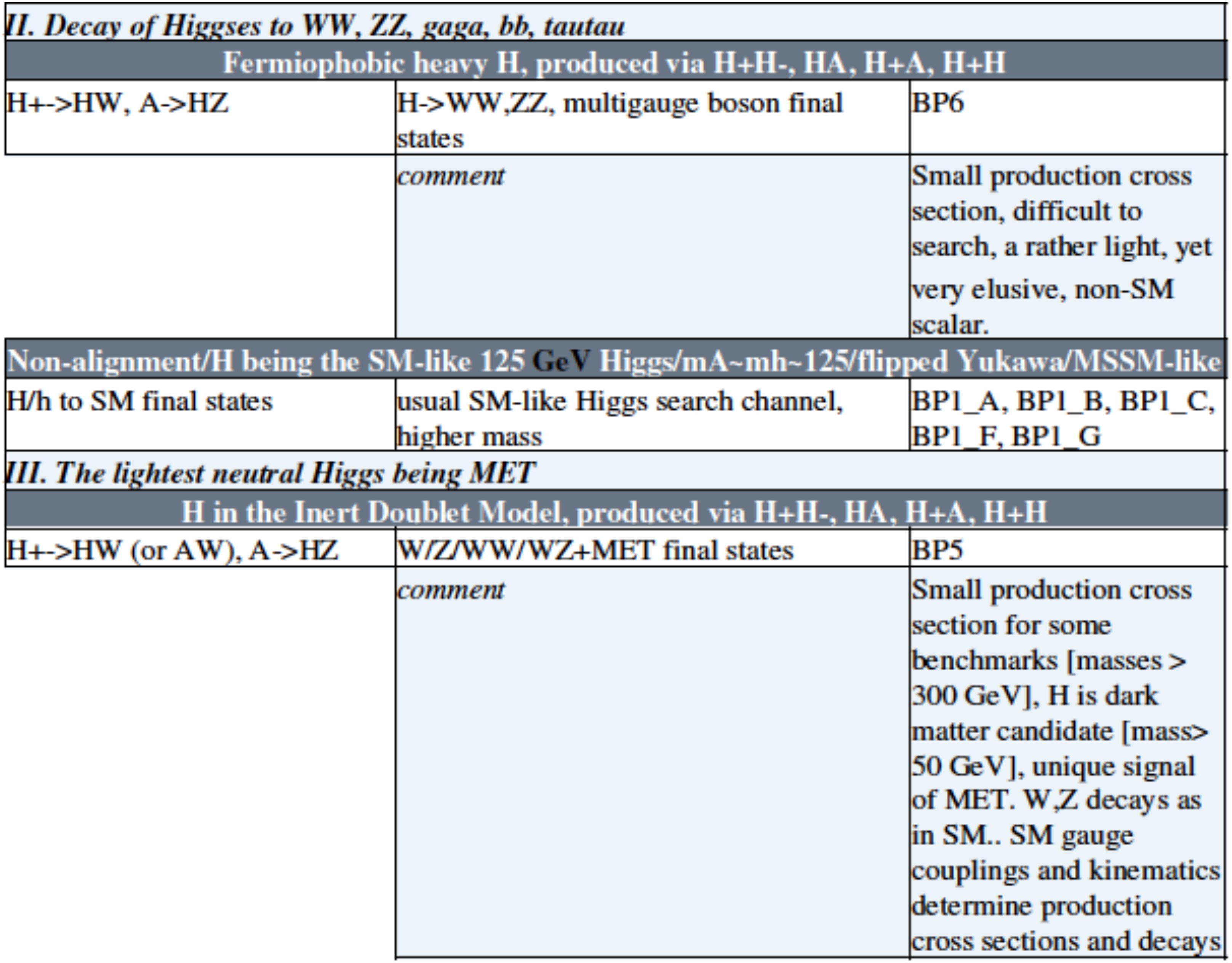
A fermiophobic limit of the 2HDM

- Type I 2HDM with sinα=0
- h is the SM-like Higgs boson with a mass of 125 GeV
- H is the fermiophobic scalar
- Since we are close to alignment

$$\cos(\beta-\alpha)\approx 0 \quad \Rightarrow \quad \frac{1}{\sqrt{1+\tan^2\beta}} << 1 \quad \Rightarrow \quad \tan\beta >> 1$$

- Relevant variables in the analysis are
  - **tanβ – departure from alignment**
  - **m_H – mass of fermiophobic scalar**
  - **ΔM – heavy scalars mass splitting**

$$\Delta M = m_H - m_A (= m_{H^\pm})$$



II. Decay of Higgses to WW, ZZ, gaga, bb, tautau		
Fermiophobic heavy H, produced via H+H-, HA, H+A, H+H		
H+->HW, A->HZ	H->WW,ZZ, multigauge boson final states	BP6
	comment	Small production cross section, difficult to search, a rather light, yet very elusive, non-SM scalar.
Non-alignment/H being the SM-like 125 GeV Higgs/mA~mh~125/flipped Yukawa/MSSM-like		
H/h to SM final states	usual SM-like Higgs search channel, higher mass	BP1_A, BP1_B, BP1_C, BP1_F, BP1_G
III. The lightest neutral Higgs being MET		
H in the Inert Doublet Model, produced via H+H-, HA, H+A, H+H		
H+->HW (or AW), A->HZ	W/Z/WW/WZ+MET final states	BP5
	comment	Small production cross section for some benchmarks [masses > 300 GeV], H is dark matter candidate [mass> 50 GeV], unique signal of MET. W,Z decays as in SM.. SM gauge couplings and kinematics determine production cross sections and decays

The benchmarks are discussed in detail in

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Benchmarks2HDM

Which planes to choose?

Inert

$$pp \to AH \to ZHH \to Z + \mathrm{MET} \qquad \text{plane: } (m_A, m_H)$$

$$pp \to H^{\pm}H^{\mp} \to W^{\pm}W^{\mp}HH \to W^{\pm}W^{\mp}MET \quad \text{plane: } (m_{H^{\pm}}, m_H)$$

cross sections reach 350 fb (first) and 90 fb (second) at 13 TeV
with BRs close to 100%

Fermiophobic

$$pp \to AH \to AVV$$

most promising but still with
very small cross section (< 2fb)

Tools

Benchmark points were obtained with the recommended tools

Higlu – Higgs production at NNLO SPIRA (1995)

SuShi – Higgs production at NNLO HARLANDER, LIEBLER, MANTLER, (2013).

HDECAY – Higgs decays DJOUADI, KALINOWSKI, SPIRA (1997) + MÜHLLEITNER (2013).

2HDMC – Higgs decays ERIKSSON, RATHSMAN, STÅL (2009)

Particular production processes (Inert and Fermiophobic), for example pp -> HA, were obtained with

MadGraph5 – Higgs production J. ALWALL EAL (2014)

2nd call – non CP-conserving 2HDM, singlet, triplet

Meeting 10 September 2015

BP7 Georgi-Machacek model benchmark *[H. Logan]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/h5plane-benchmark.pdf

BP8 Complex 2HDM benchmarks *[D. Fontes, J.C. Romao, R. Santos and J.P. Silva]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-C2HDM.pdf

BP9 Flavour-changing 2HDM benchmarks *[F.J. Botella, G.C. Branco, M. Nebot and M. Rebelo]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-FCNC2HDM.pdf

BP10 Real and complex singlet benchmarks *[R. Costa, M. Muhlleitner, M.O.P. Sampaio and R. Santos]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/BenchmarksCxSM_and_RxSM.pdf

BP11 Singlet benchmarks *[T. Robens and T.Stefaniak]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmarks_robens_stefaniak.pdf

BP8 CP-violating 2HDM (C2HDM)

The softly broken Z_2 symmetric CP-violating potential

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right]$$

- m^2_{12} and λ_5 complex

Free parameters

Parameter	2HDM (Z_2 basis)	C2HDM (Z_2 basis)
Masses	m_h, m_H, m_A, $m_{H\pm}$	m_1, m_2, $m_{H\pm}$
Angles	$\tan\beta$, $(\beta-\alpha)$	$\tan\beta$, α_1, α_2, α_3
Other	m_{12}^2	$\mathrm{Re}(m_{12}^2)$

Lightest Higgs couplings

$$\boxed{\alpha_1 = \alpha + \pi / 2}$$

to gauge bosons

$$\boxed{g_{2HDM}^{hVV} = \sin(\beta - \alpha)\ g_{SM}^{hVV}} \qquad V = W, Z$$

CP-CONSERVING

$$\boxed{g_{C2HDM}^{hVV} = C\ g_{SM}^{hVV} = (c_\beta R_{11} + s_\beta R_{12})\ g_{SM}^{hVV} = \cos(\alpha_2)\cos(\beta - \alpha_1)\ g_{SM}^{hVV}}$$

CP-VIOLATING

$$\boxed{g_{C2HDM}^{hVV} = \cos(\alpha_2)\ g_{2HDM}^{hVV}}$$

$$C \equiv c_\beta R_{11} + s_\beta R_{12}$$

$$|s_2| = 0 \ \Rightarrow\ h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \ \Rightarrow\ h_1 \text{ is a pure pseudoscalar}$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 s_3 \end{pmatrix}$$

Lightest Higgs couplings

Yukawa couplings

$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases}$$

$$R = \begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -(c_1s_2s_3 + s_1c_3) & c_1c_3 - s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3 + s_1s_3 & -(c_1s_3 + s_1s_2c_3) & c_2s_3 \end{pmatrix}$$

CP-CONSERVING

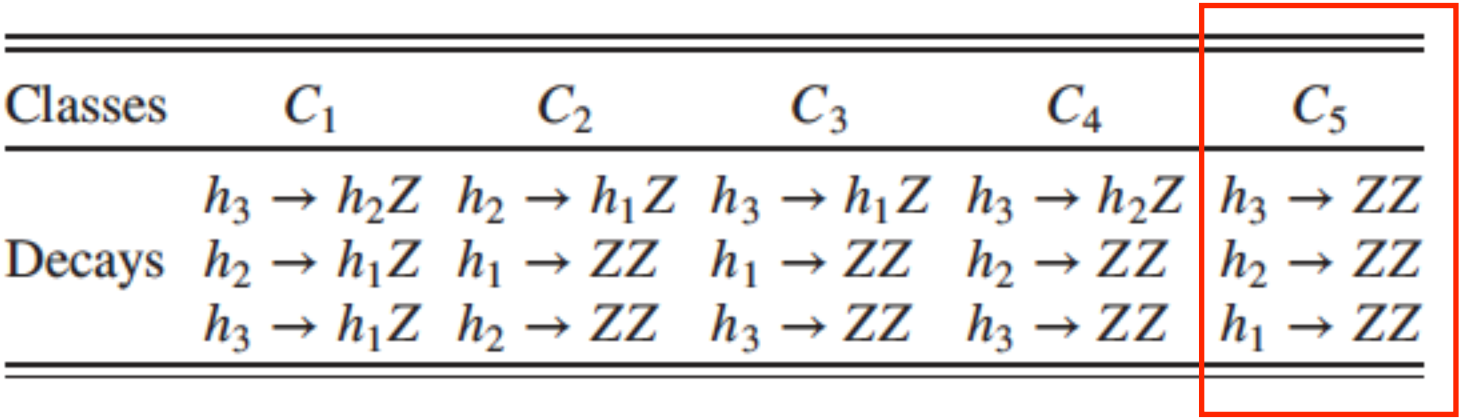
	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
Down	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$
Leptons	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$

$$\alpha_1 = \alpha + \pi/2$$

CP-VIOLATING

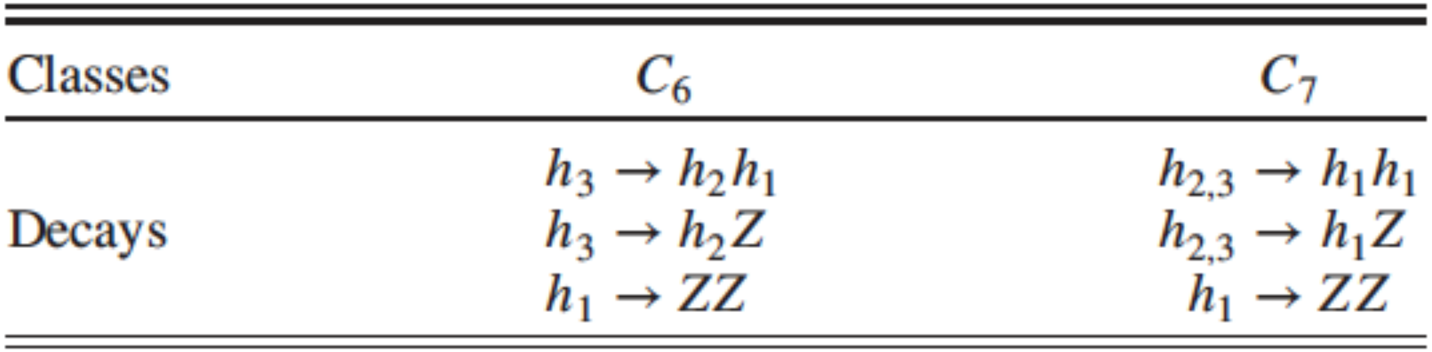
	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta\frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta\frac{R_{13}}{c_\beta}\gamma_5$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta\frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta\frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta\frac{R_{13}}{s_\beta}\gamma_5$

Classes of CP-violating processes



Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \to h_2 Z$	$h_2 \to h_1 Z$	$h_3 \to h_1 Z$	$h_3 \to h_2 Z$	$h_3 \to ZZ$
	$h_2 \to h_1 Z$	$h_1 \to ZZ$	$h_1 \to ZZ$	$h_2 \to ZZ$	$h_2 \to ZZ$
	$h_3 \to h_1 Z$	$h_2 \to ZZ$	$h_3 \to ZZ$	$h_3 \to ZZ$	$h_1 \to ZZ$

In 2HDMs



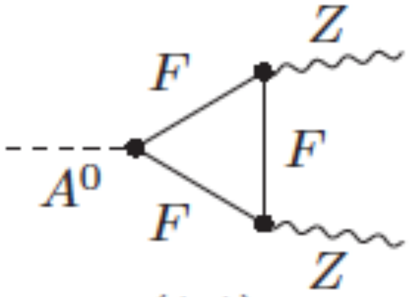
Classes	C_6	C_7
Decays	$h_3 \to h_2 h_1$	$h_{2,3} \to h_1 h_1$
	$h_3 \to h_2 Z$	$h_{2,3} \to h_1 Z$
	$h_1 \to ZZ$	$h_1 \to ZZ$

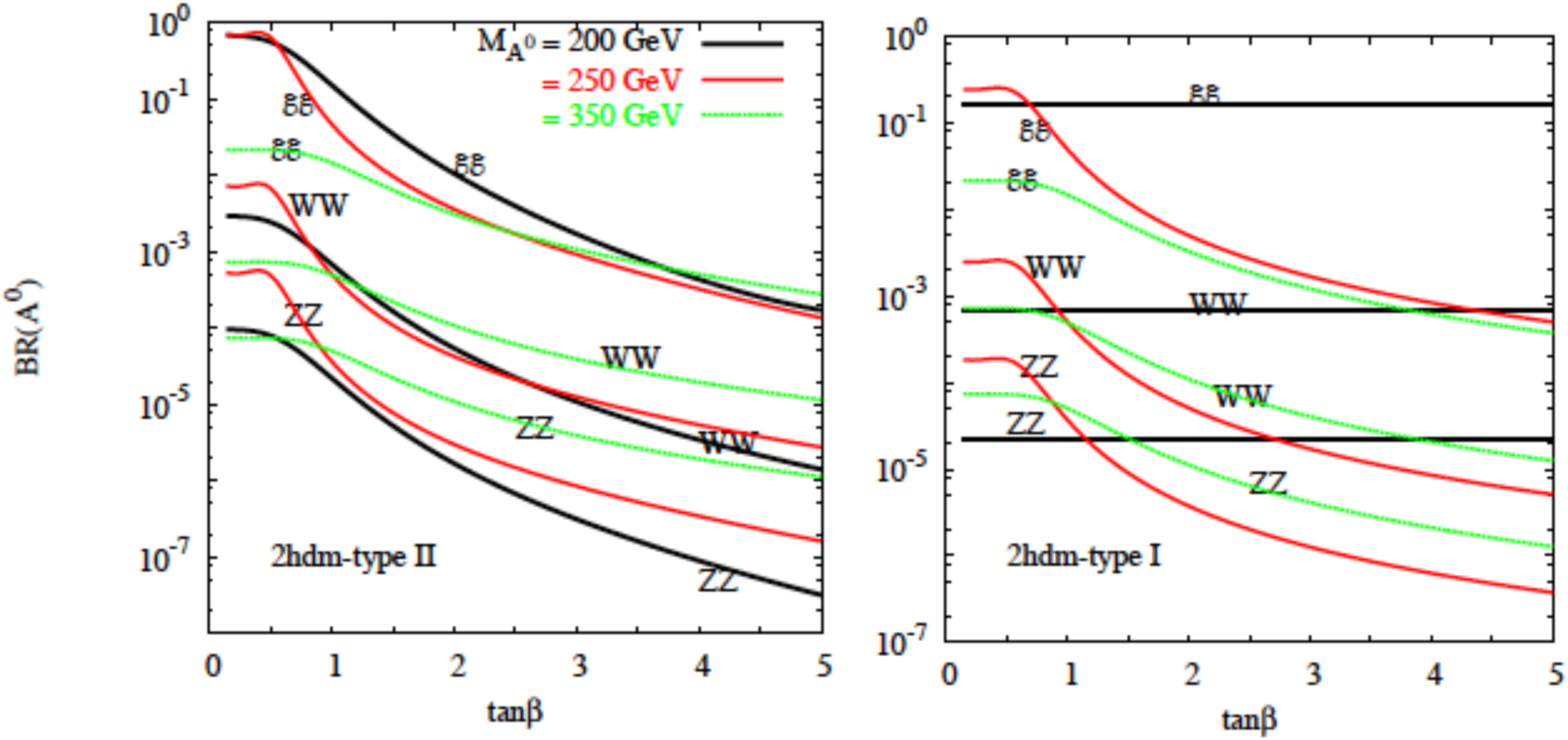
Classes involving scalar to two scalars decays

Fontes, Romão, RS, Silva (2015).

For each particular model one should check

$$A \to ZZ\ (W^+W^-)$$





Arhrib, Benbrik, Field (2006).

CP-violating class C2 (and C3 and C4)

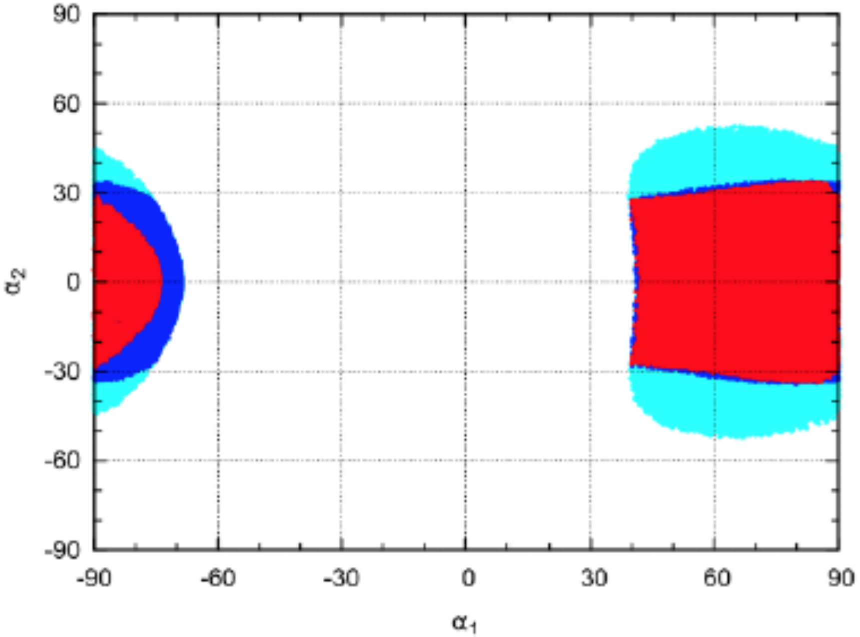
$h_2 \to h_3 \quad h_1 \to h_2$

$$h_1 \to ZZ \quad \Rightarrow \quad \mathrm{CP}(h_1) = 1$$

$$h_2 \to ZZ \quad \Rightarrow \quad \mathrm{CP}(h_2) = 1$$

$$h_2 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_1) \neq \mathrm{CP}(h_2)$$

Observing the three decays constitutes a "model independent" sign of CP-violation.



$$\chi = \frac{BR(h_2 \to ZZ)}{BR(h_2 \to h_1 Z)}$$

The benchmark plane is (m_2, χ)

α_2 is already constrained by the first decay. The constraints from the other two decays could be combined in a (m_2, $\sin\alpha_2$) plane.

CP-violating class C1

$$h_3 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_3) = -\,\mathrm{CP}(h_1)$$

$$h_2 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_2) = -\,\mathrm{CP}(h_1)$$

$$h_3 \to h_2 Z \quad \Rightarrow \quad \mathrm{CP}(h_2) \neq \mathrm{CP}(h_3)$$

Observing the three decays constitutes a "model independent" sign of CP-violation.

$$\chi = \frac{BR(h_3 \to h_1 Z)}{BR(h_3 \to h_1 ZZ)}$$

- The benchmark plane is (m_2, m_3) with χ as a parameter.
- Another benchmark plane is (m_2, χ) with m_3 as a parameter.

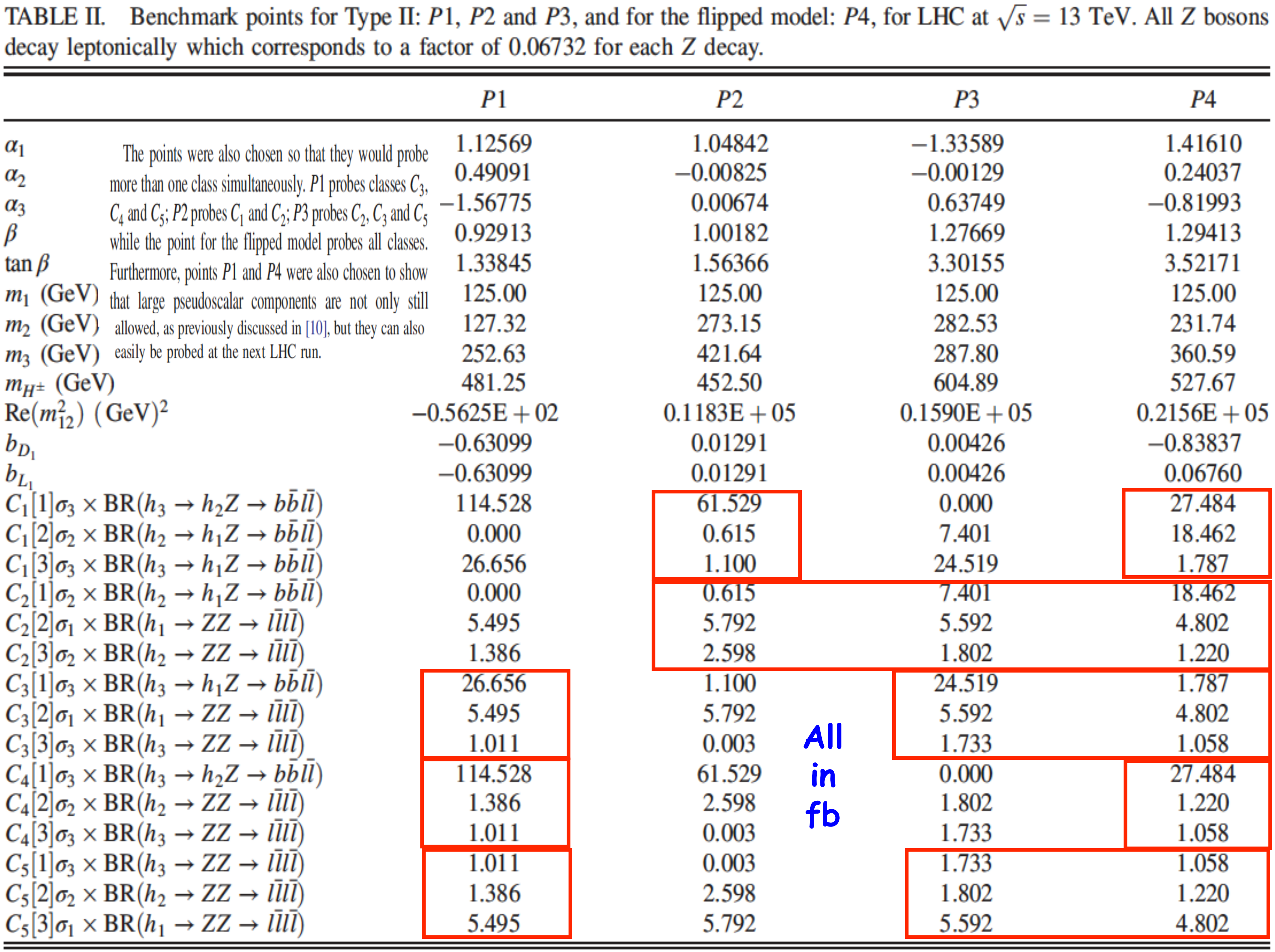


TABLE II. Benchmark points for Type II: $P1$, $P2$ and $P3$, and for the flipped model: $P4$, for LHC at $\sqrt{s} = 13$ TeV. All Z bosons decay leptonically which corresponds to a factor of 0.06732 for each Z decay.

The points were also chosen so that they would probe more than one class simultaneously. $P1$ probes classes C_3, C_4 and C_5; $P2$ probes C_1 and C_2; $P3$ probes C_2, C_3 and C_5 while the point for the flipped model probes all classes. Furthermore, points $P1$ and $P4$ were also chosen to show that large pseudoscalar components are not only still allowed, as previously discussed in [10], but they can also easily be probed at the next LHC run.

	$P1$	$P2$	$P3$	$P4$
α_1	1.12569	1.04842	−1.33589	1.41610
α_2	0.49091	−0.00825	−0.00129	0.24037
α_3	−1.56775	0.00674	0.63749	−0.81993
β	0.92913	1.00182	1.27669	1.29413
$\tan\beta$	1.33845	1.56366	3.30155	3.52171
m_1 (GeV)	125.00	125.00	125.00	125.00
m_2 (GeV)	127.32	273.15	282.53	231.74
m_3 (GeV)	252.63	421.64	287.80	360.59
$m_{H^\pm}$ (GeV)	481.25	452.50	604.89	527.67
$\mathrm{Re}(m_{12}^2)$ $(\mathrm{GeV})^2$	−0.5625E + 02	0.1183E + 05	0.1590E + 05	0.2156E + 05
b_{D_1}	−0.63099	0.01291	0.00426	−0.83837
b_{L_1}	−0.63099	0.01291	0.00426	0.06760
$C_1[1]\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	114.528	61.529	0.000	27.484
$C_1[2]\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	0.000	0.615	7.401	18.462
$C_1[3]\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	26.656	1.100	24.519	1.787
$C_2[1]\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	0.000	0.615	7.401	18.462
$C_2[2]\sigma_1 \times \mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495	5.792	5.592	4.802
$C_2[3]\sigma_2 \times \mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386	2.598	1.802	1.220
$C_3[1]\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	26.656	1.100	24.519	1.787
$C_3[2]\sigma_1 \times \mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495	5.792	5.592	4.802
$C_3[3]\sigma_3 \times \mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011	0.003	1.733	1.058
$C_4[1]\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	114.528	61.529	0.000	27.484
$C_4[2]\sigma_2 \times \mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386	2.598	1.802	1.220
$C_4[3]\sigma_3 \times \mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011	0.003	1.733	1.058
$C_5[1]\sigma_3 \times \mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011	0.003	1.733	1.058
$C_5[2]\sigma_2 \times \mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386	2.598	1.802	1.220
$C_5[3]\sigma_1 \times \mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495	5.792	5.592	4.802

All in fb

Other combinations not possible in the CP-conserving 2HDM

$$\boxed{h_1 \to ZZ \quad \Rightarrow \quad \mathrm{CP}(h_1) = 1}$$

Observed

$$\boxed{h_3 \to h_2 h_1 \quad \Rightarrow \quad \mathrm{CP}(h_3) = \mathrm{CP}(h_2)\ \mathrm{CP}(h_1) = \mathrm{CP}(h_2)}$$

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad \mathrm{CP}(h_3) = -\ \mathrm{CP}(h_2)$	None	C2HDM, ...
$h_{2(3)} \to h_1 Z \quad \mathrm{CP}(h_{2(3)}) = -1$	2 CP-odd	C2HDM, ...
$h_2 \to ZZ \quad \mathrm{CP}(h_2) = 1$	3 CP-even	C2HDM, cxSM, ...

Class C7

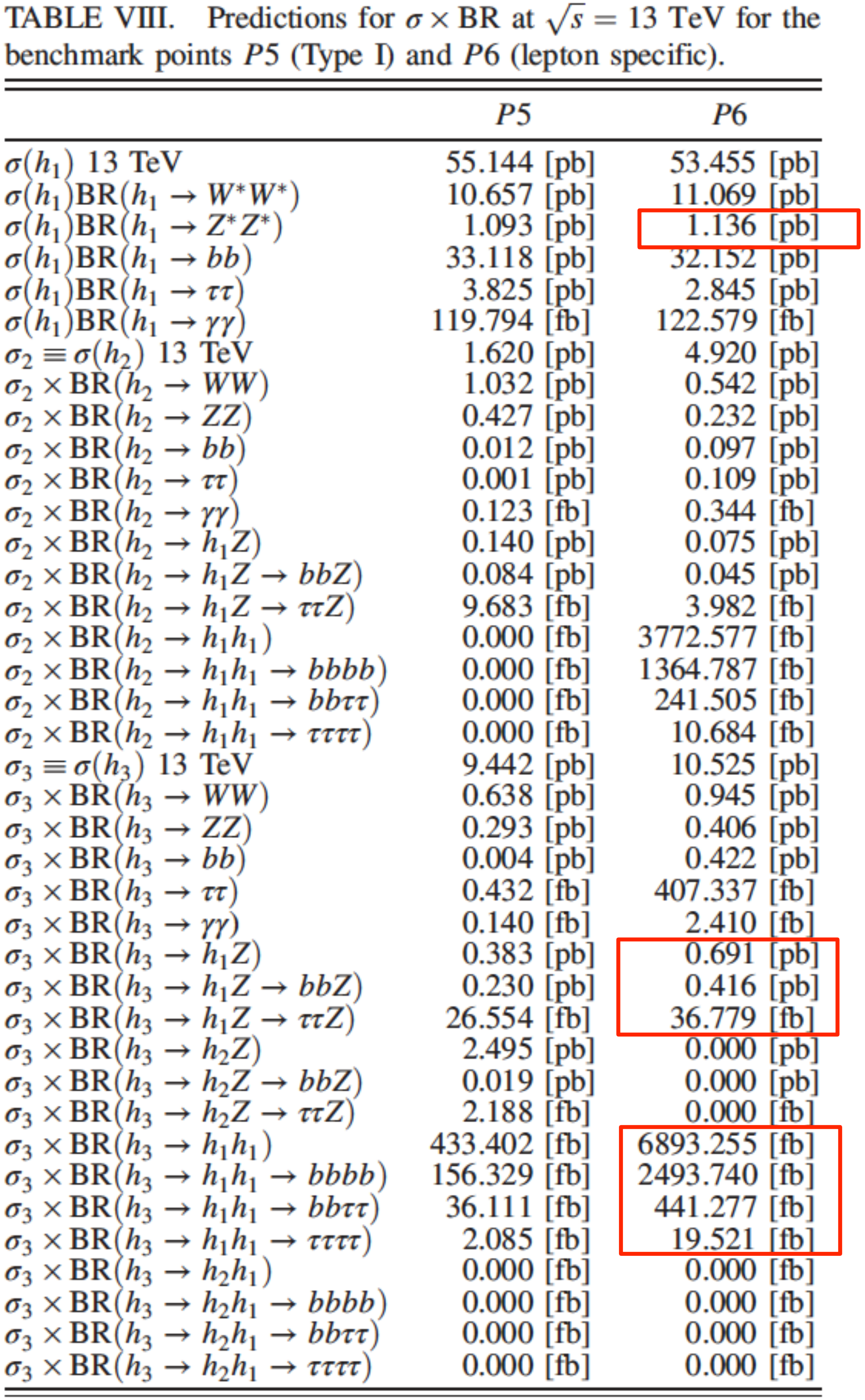


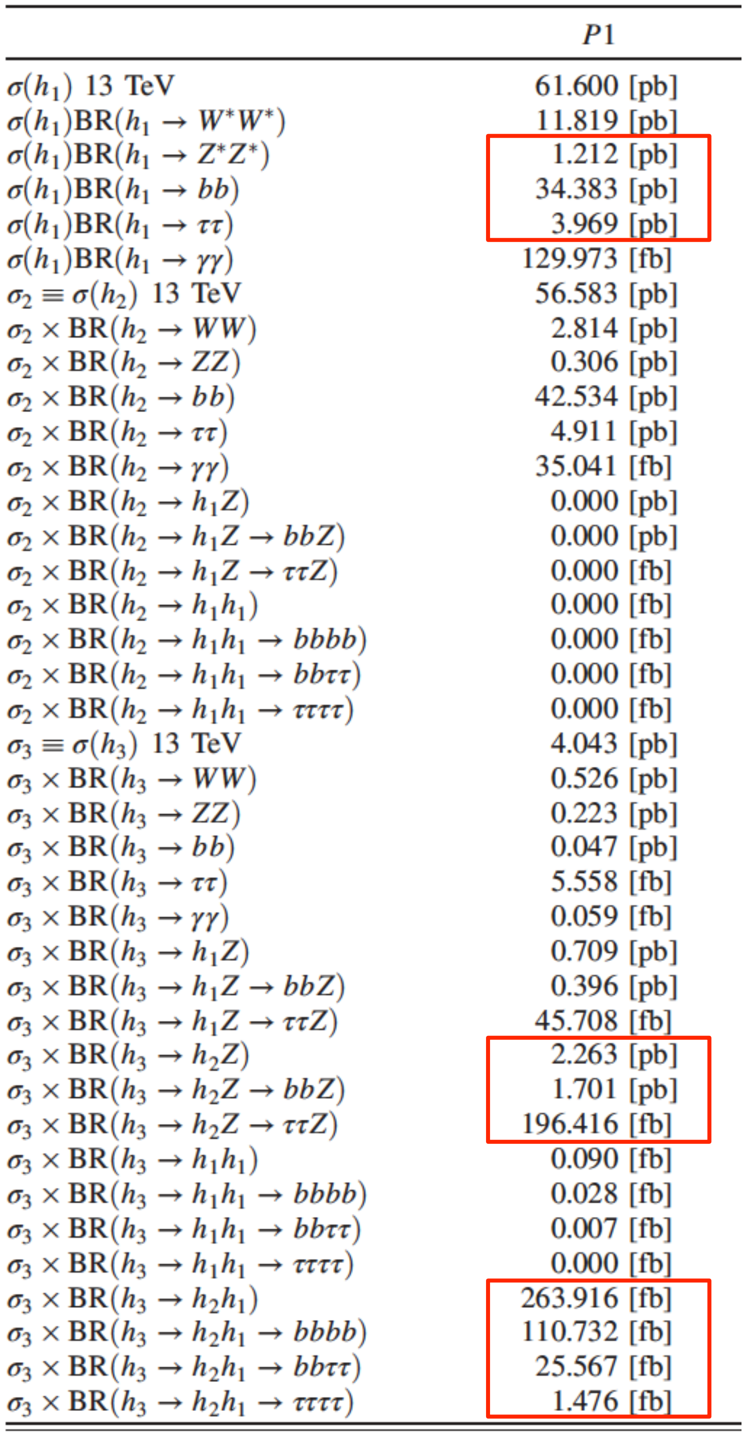
TABLE VIII. Predictions for $\sigma \times \mathrm{BR}$ at $\sqrt{s} = 13$ TeV for the benchmark points *P*5 (Type I) and *P*6 (lepton specific).

	*P*5	*P*6
$\sigma(h_1)$ 13 TeV	55.144 [pb]	53.455 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to W^*W^*)$	10.657 [pb]	11.069 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to Z^*Z^*)$	1.093 [pb]	1.136 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to bb)$	33.118 [pb]	32.152 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to \tau\tau)$	3.825 [pb]	2.845 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to \gamma\gamma)$	119.794 [fb]	122.579 [fb]
$\sigma_2 \equiv \sigma(h_2)$ 13 TeV	1.620 [pb]	4.920 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	1.032 [pb]	0.542 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	0.427 [pb]	0.232 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.012 [pb]	0.097 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.001 [pb]	0.109 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.123 [fb]	0.344 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z)$	0.140 [pb]	0.075 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to bbZ)$	0.084 [pb]	0.045 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to \tau\tau Z)$	9.683 [fb]	3.982 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	0.000 [fb]	3772.577 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.000 [fb]	1364.787 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	0.000 [fb]	241.505 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]	10.684 [fb]
$\sigma_3 \equiv \sigma(h_3)$ 13 TeV	9.442 [pb]	10.525 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to WW)$	0.638 [pb]	0.945 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$	0.293 [pb]	0.406 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to bb)$	0.004 [pb]	0.422 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$	0.432 [fb]	407.337 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$	0.140 [fb]	2.410 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z)$	0.383 [pb]	0.691 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to bbZ)$	0.230 [pb]	0.416 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to \tau\tau Z)$	26.554 [fb]	36.779 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z)$	2.495 [pb]	0.000 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to bbZ)$	0.019 [pb]	0.000 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to \tau\tau Z)$	2.188 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	433.402 [fb]	6893.255 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$	156.329 [fb]	2493.740 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	36.111 [fb]	441.277 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	2.085 [fb]	19.521 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bbbb)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bb\tau\tau)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]	0.000 [fb]

$$h_1 \to ZZ \quad \Rightarrow \quad \mathrm{CP}(h_1) = 1$$

$$h_3 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_3) = -\,\mathrm{CP}(h_1) = -1$$

$$h_3 \to h_1 h_1 \quad \Rightarrow \quad \mathrm{CP}(h_3) = 1$$



	$P1$
$\sigma(h_1)$ 13 TeV	61.600 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to W^*W^*)$	11.819 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to Z^*Z^*)$	1.212 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to bb)$	34.383 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to \tau\tau)$	3.969 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to \gamma\gamma)$	129.973 [fb]
$\sigma_2 \equiv \sigma(h_2)$ 13 TeV	56.583 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	2.814 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	0.306 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	42.534 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	4.911 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	35.041 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z)$	0.000 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to bbZ)$	0.000 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to \tau\tau Z)$	0.000 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	0.000 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.000 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	0.000 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]
$\sigma_3 \equiv \sigma(h_3)$ 13 TeV	4.043 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to WW)$	0.526 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$	0.223 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to bb)$	0.047 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$	5.558 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$	0.059 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z)$	0.709 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to bbZ)$	0.396 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to \tau\tau Z)$	45.708 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z)$	2.263 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to bbZ)$	1.701 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to \tau\tau Z)$	196.416 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	0.090 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$	0.028 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	0.007 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1)$	263.916 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bbbb)$	110.732 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bb\tau\tau)$	25.567 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to \tau\tau\tau\tau)$	1.476 [fb]

Class C6

$$h_1 \to ZZ \quad \Rightarrow \quad \mathrm{CP}(h_1) = 1$$

$$h_3 \to h_2 Z \quad \Rightarrow \quad \mathrm{CP}(h_3) = -\,\mathrm{CP}(h_2)$$

$$h_3 \to h_2 h_1 \quad \Rightarrow \quad \mathrm{CP}(h_3) = \mathrm{CP}(h_2)$$

BP9 BGL models?

Branco, Grimus, Lavoura (1996)

The Yukawa Lagrangian of BLV models is

$$\begin{aligned}\mathcal{L}_Y = &- \overline{Q_L^0}\left[\Gamma_1\,\Phi_1 + \Gamma_2\,\Phi_2\right] d_R^0 - \overline{Q_L^0}\left[\Delta_1\,\tilde{\Phi}_1 + \Delta_2\,\tilde{\Phi}_2\right] u_R^0 \\ &- \overline{L_L^0}\left[\Pi_1\,\Phi_1 + \Pi_2\,\Phi_2\right] l_R^0 - \overline{L_L^0}\left[\Sigma_1\,\tilde{\Phi}_1 + \Sigma_2\,\tilde{\Phi}_2\right] \nu_R^0 + \text{h.c.},\end{aligned}$$

Invariance under

$$Q_{Lj}^0 \mapsto \exp\left(i\tau\right) Q_{Lj}^0\,, \qquad u_{Rj}^0 \mapsto \exp\left(i2\tau\right) u_{Rj}^0\,, \qquad \Phi_2 \mapsto \exp\left(i\tau\right)\Phi_2$$

leads to Higgs FCNC in the down sector. Invariance under

$$Q_{Lj}^0 \mapsto \exp\left(i\tau\right) Q_{Lj}^0\,, \qquad d_{Rj}^0 \mapsto \exp\left(i2\tau\right) d_{Rj}^0\,, \quad \Phi_2 \mapsto \exp\left(-i\tau\right)\Phi_2$$

leads to Higgs FCNC in the up sector. The **potential** is

$$\begin{aligned}V = &\ \mu_1\Phi_1^\dagger\Phi_1 + \mu_2\Phi_2^\dagger\Phi_2 - m_{12}\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + 2\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) \\ &+ 2\lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2,\end{aligned}$$

If Higgs FCNC is in the up sector the couplings are

$$Y^U_{qt}(d_\rho) = -V_{q\rho}V^*_{t\rho}\,\frac{m_t}{v}\,c_{\beta\alpha}(t_\beta + t_\beta^{-1})\,, \quad q = u, c\,.$$

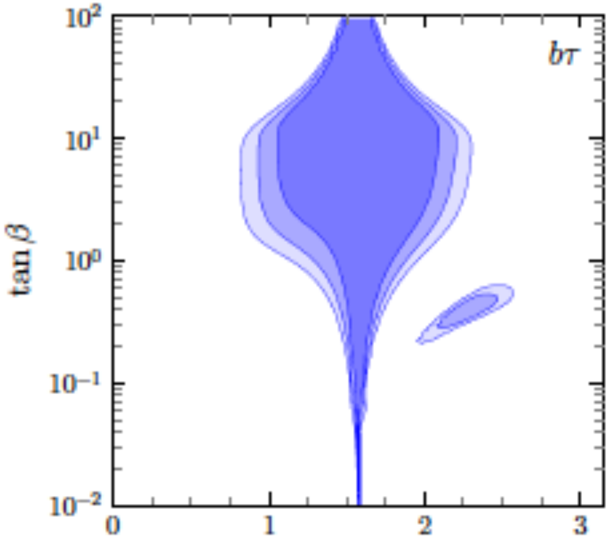
which leads to the top quark decay widths

$$\Gamma_{(d_\rho)}(t \to hq) = \frac{m_t^3}{32\pi v^2}\left(1 - \frac{m_h^2}{m_t^2}\right)^2 |V_{q\rho}|^2 |V_{t\rho}|^2 c^2_{\beta\alpha}(t_\beta + t_\beta^{-1})^2$$

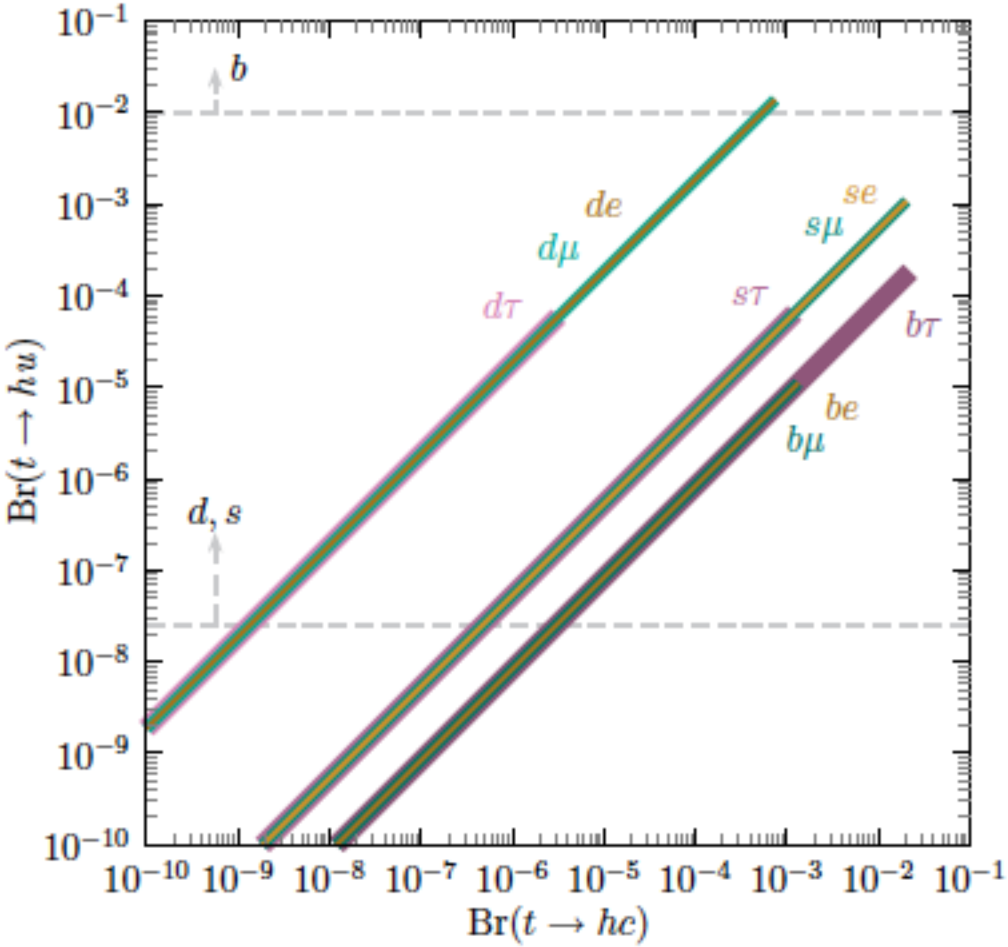
withe angles alpha and beta defined in the usual way.

"So we fix our benchmark scenarios by trying to maximise these new effects but in agreement with other low energy flavour constraints. Also we choose those scenarios where important signals can show up at LHC, although in some cases some of the observables could be more relevant for a future linear collider."

Example: the (b,τ) model near decoupling



(d) Model $b\,\tau$



MODEL	$\lvert c_{\beta\alpha}\rvert$	$\tan\beta$	$m_H \sim m_A \sim m_{H^\pm}$	m_h	Interesting Channels
(b,τ)	≤ 0.17	$25-100$	≥ 600	125	$t\to hq, h\to b\bar{b}, \tau\bar{\tau}$

Botella, ranco, Nebot, Rebelo (2015)

BP10 and BP11 Scalar singlet

CxSM – dark matter AND new visible scalars

SM plus $\mathbb{S} = (S + iA)/\sqrt{2}$, with residual $\mathbb{Z}_2$ symmetry $A \to -A$ after $\cancel{U(1)}$ symmetry by soft terms (in parenthesis)

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1 \mathbb{S} + c.c. \right)$$

- $\mathbb{Z}_2$ phase ($v_S \neq 0$, $v_A = 0$): 2 scalars mix + 1 dark

$$\begin{pmatrix} h_1 \\ h_2 \\ A \end{pmatrix} = \begin{pmatrix} \kappa_1 & -\sin\alpha & 0 \\ \kappa_2 & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix}$$

- $\cancel{\mathbb{Z}_2}$ phase ($v_S \neq 0$, $v_A \neq 0$): 3 scalars mix

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \kappa_1 & R_{1S} & R_{1A} \\ \kappa_2 & R_{2S} & R_{2A} \\ \kappa_3 & R_{3S} & R_{3A} \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix}$$

- Many OBSs related to SM up to κ_a factors (Ex. $\frac{\sigma_a}{\sigma_{SM}} \propto \kappa_a^2$)

RxSM – dark matter OR new visible scalar

SM plus S, with $\mathbb{Z}_2$ symmetry $S \to -S$

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\lambda_{HS}}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4$$

- $\cancel{\mathbb{Z}_2}$ phase ($v_S \neq 0$): 2 scalars mix

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- $\mathbb{Z}_2$ phase ($v_S = 0$): 1 Higgs + 1 dark

$$\begin{pmatrix} h_1 \\ S \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- We ignore dark phase!

Suggested Benchmarks – CxSM Dark

	CxSM.D1	CxSM.D2	CxSM.D3
$\star\ m_1$ (GeV)	125.4	125.4	49.116
$\star\ m_2$ (GeV)	456.57	339.77	125.4
$\star\ m_A$ (GeV)	52.98	77.022	65.054
$\star\ \alpha$	-0.39506	-0.50029	1.4617
$\Omega_A h^2$	0.115	0.116	0.115
μ_{h_1}	0.852	0.77	0.0118
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	26.9 [pb]	24.3 [pb]	2.14 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.59 [pb]	4.84 [pb]	0.0346 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	577 [fb]	609 [fb]	0.011 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	14.1 [pb]	14.9 [pb]	1.87 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.35 [pb]	1.43 [pb]	148 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	49.7 [fb]	52.5 [fb]	0.608 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to AA)$	3.84 [pb]	0	0
μ_{h_2}	0.0977	0.135	0.743
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	698 [fb]	1.6 [pb]	31.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	251 [fb]	642 [fb]	4.67 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	119 [fb]	292 [fb]	587 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.0764 [fb]	0.432 [fb]	14.3 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	$<$ 0.01 [fb]	0.0501 [fb]	1.38 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	$<$ 0.01 [fb]	$<$ 0.01 [fb]	50.6 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	155 [fb]	429 [fb]	7.74 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	42.7 [fb]	160 [fb]	5.89 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	8.19 [fb]	30.8 [fb]	932 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	27.8 [fb]	105 [fb]	0.218 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	0.302 [fb]	1.13 [fb]	3.83 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.393 [fb]	1.48 [fb]	36.9 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to AA)$	0.0822 [pb]	0.233 [pb]	0
$\mu_{\mathrm{stability}}$ (GeV)	10^{12}	10^{14}	10^{8}

Suggested Benchmarks – CxSM Broken

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
$\star\ m_1$ (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
$\star\ m_3$ (GeV)	462.4	271.3	345.5	255.2	125.4
$\star\ \alpha_1$	-0.04867	0.03148	-1.071	-0.7888	-1.169
$\star\ \alpha_2$	0.4739	-0.5707	1.126	0.7717	1.24
$\star\ \alpha_3$	-0.4763	-0.3888	-0.005447	-0.1945	1.044
μ_{h_1}	0.79	0.707	0.0426	0.255	0.0161
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	24.9 [pb]	22.3 [pb]	5.67 [pb]	12.5 [pb]	4.19 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.97 [pb]	4.45 [pb]	0.262 [fb]	87.4 [fb]	0.0226 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	625 [fb]	560 [fb]	0.0807 [fb]	10 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	15.2 [pb]	13.6 [pb]	4.91 [pb]	10.2 [pb]	3.67 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.46 [pb]	1.31 [pb]	401 [fb]	936 [fb]	281 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	53.8 [fb]	48.2 [fb]	2.26 [fb]	17.4 [fb]	0.831 [fb]
μ_{h_2}	0.0636	0.0547	0.768	0.626	0.0205
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	559 [fb]	577 [fb]	24.4 [pb]	19.7 [pb]	1.88 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	390 [fb]	408 [fb]	4.87 [pb]	3.95 [pb]	0.342 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	167 [fb]	167 [fb]	613 [fb]	497 [fb]	0.0998 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.601 [fb]	0.928 [fb]	14.8 [pb]	12.1 [pb]	1.61 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.0663 [fb]	0.1 [fb]	1.42 [pb]	1.16 [pb]	137 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0122 [fb]	0.0186 [fb]	52.4 [fb]	42.7 [fb]	1.15 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	0.0467 [fb]	0	195 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.0175 [fb]	0	146 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	$<$ 0.01 [fb]	0	23.9 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	0.0114 [fb]	0	0.0156 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.134 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.976 [fb]	0	0

Suggested Benchmarks – CxSM Broken

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
⋆ m_1 (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
⋆ m_3 (GeV)	462.4	271.3	345.5	255.2	125.4
μ_{h_3}	0.0774	0.0868	0.111	0.0273	0.777
$\sigma_3 \equiv \sigma(gg \to h_3)$ 13 TeV	659 [fb]	1.95 [pb]	1.31 [pb]	1.07 [pb]	30.4 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to WW)$	189 [fb]	496 [fb]	537 [fb]	172 [fb]	4.89 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$	89.7 [fb]	215 [fb]	245 [fb]	73.2 [fb]	615 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to bb)$	0.0558 [fb]	0.656 [fb]	0.345 [fb]	0.277 [fb]	15 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$	$<$ 0.01 [fb]	0.073 [fb]	0.0401 [fb]	0.0305 [fb]	1.44 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$	$<$ 0.01 [fb]	0.0133 [fb]	$<$ 0.01 [fb]	$<$ 0.01 [fb]	53 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	3.75 [fb]	1.24 [pb]	280 [fb]	415 [fb]	5.47 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$	1.4 [fb]	464 [fb]	210 [fb]	279 [fb]	4.2 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	0.269 [fb]	89 [fb]	34.4 [fb]	51 [fb]	643 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbWW)$	0.915 [fb]	302 [fb]	0.0224 [fb]	4.76 [fb]	0.0518 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	3.28 [fb]	0.193 [fb]	0.948 [fb]	1.9 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.0129 [fb]	4.27 [fb]	1.41 [fb]	2.33 [fb]	24.6 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2)$	307 [fb]	0	83.5 [fb]	408 [fb]	401 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbbb)$	0.202 [fb]	0	43.8 [fb]	204 [fb]	301 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\tau\tau)$	0.0417 [fb]	0	7.78 [fb]	38.3 [fb]	48.7 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbWW)$	131 [fb]	0	14.4 [fb]	68.7 [fb]	0.0657 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.175 [fb]	1.07 [fb]	0.284 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.344 [fb]	1.79 [fb]	1.96 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2)$	0	0	151 [fb]	0.318 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbbb)$	0	0	55.5 [fb]	0.119 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\tau\tau)$	0	0	10.6 [fb]	0.0228 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbWW)$	0	0	36.6 [fb]	0.0776 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\gamma\gamma)$	0	0	0.393 [fb]	$<$ 0.01 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to \tau\tau\tau\tau)$	0	0	0.511 [fb]	$<$ 0.01 [fb]	0
$\mu_{\text{RGE stability}}$ (GeV)	10^4	10^5	10^{16}	10^9	10^7

Suggested Benchmarks – RxSM Broken

	RxSM.B1	RxSM.B2	RxSM.B3	RxSM.B4
$\star\ m_1$ (GeV)	125.4	125.4	36.283	117.19
$\star\ m_2$ (GeV)	279.65	176.3	125.4	125.4
$\star\ \alpha$	-0.54065	-0.46964	1.4272	-0.97629
μ_{h_1}	0.735	0.795	0.0205	0.314
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	23.2 [pb]	25.1 [pb]	7.26 [pb]	11.2 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.62 [pb]	5 [pb]	0.0162 [fb]	1.07 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	581 [fb]	629 [fb]	$<$ 0.01 [fb]	115 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	14.2 [pb]	15.3 [pb]	6.38 [pb]	8 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.36 [pb]	1.47 [pb]	475 [fb]	758 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	50.1 [fb]	54.2 [fb]	1.08 [fb]	22.7 [fb]
μ_{h_2}	0.148	0.205	0.66	0.686
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	2.09 [pb]	3.48 [pb]	30.9 [pb]	21.6 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	810 [fb]	3.31 [pb]	4.15 [pb]	4.32 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	354 [fb]	130 [fb]	522 [fb]	543 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.972 [fb]	24.6 [fb]	12.7 [pb]	13.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.109 [fb]	2.52 [fb]	1.22 [pb]	1.27 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0196 [fb]	0.429 [fb]	45 [fb]	46.8 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	920 [fb]	0	10.1 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	344 [fb]	0	7.79 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	66.1 [fb]	0	1.16 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	225 [fb]	0	0.0395 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	2.43 [fb]	0	2.63 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	3.17 [fb]	0	43.2 [fb]	0

Tools

Benchmark points were obtained with the tools

Higlu – Higgs production at NNLO — Spira (1995)

SuShi – Higgs production at NNLO — Harlander, Liebler, Mantler, (2013).

sHDECAY – Higgs decays — Djouadi, Kalinowski, Spira (1997) + Costa, Sampaio, RS, Mühlleitner (2015).

ScannerS – Phenomenological constraints; interfaced with — Coimbra, Sampaio, RS, (2013).

- **HiggsBounds** – Limits from Higgs searches at LEP, Tevatron and LHC
- **HiggsSignals** – Signal rates at the Tevatron and LHC

Bechtle, Brein, Heinemeyer, Stål, Stefaniak, Weiglein, Williams (2010-2015)

Plans

- Update benchmark points
- Tools?

    - discuss benchmark points
    - decide on benchmark planes

- Prepare contribution for YR4

Back-up slides

CP assignments

$$(CP)\, Z_\mu\, (CP)^\dagger = -Z^\mu$$

$$h_i \to h_j Z \qquad \begin{cases} \text{initial state} & s(h_i) = 0 \Rightarrow J_i = 0 \\ \text{final state} & s(h_j) \otimes s(Z) = 1 \end{cases}$$

One needs

$$J_f = s_f \otimes L_f = 0 \Rightarrow L_f = 1$$

and

$$CP(h_i) = CP(h_j)\, CP(Z)\, (-1)^{L_f} = -\, CP(h_j)$$

CP assignments

If C and P are good quantum numbers, the vertex hAZ forces

$$C(Z) = -1 \Rightarrow C(h) \ = -C(A)$$

$$P(Z) = -1 \Rightarrow P(h) \ = P(A)$$

and

$$CP(Z) = 1 \Rightarrow CP(h) \ = -CP(A)$$

because

$$CP(hAZ) = -1 \qquad\qquad CP(\partial hAZ) = 1$$

The vertex hZZ (which has no derivatives) forces

$$C(h) \ = P(h) = 1 \quad \Rightarrow \quad C(A) = -1; \ \ P(A) = 1$$

Singlets & the Higgs portal

How?

- Scalar sector prone to coupling to hidden sectors!

$$V = V_{SM}(H^\dagger H) + H^\dagger H \times \mathcal{O}_\delta^{(2)}(\phi_i) + V_{New}(\phi_i)$$

- Couplings to SM through mixing

$$\text{Higgs fluctuation} \leftarrow h = \sum_a \kappa_a H_a \, , \; \sum_a |\kappa_a|^2 = 1$$

Why?

- Simple parametrization of DM
- V_{eff} @ $T \neq 0$ can be compatible with EW-Baryogenesis
- Improve stability of SM @ high energies

Scan conditions – PHENO TESTS [arXiv:1411.4048]

Phenomenological constraints imposed using ScannerS:

`scanners.hepforge.org`

- Electroweak precision observables – STU
- Collider data (LEP, Tevatron, LHC) HiggsBounds/Signals
- Dark matter relic density below Planck measurement & bounds from LUX on σ_{SI} (micrOMEGAs)

⇒ **Decay widths – adaptation of HDECAY → sHDECAY.**

`www.itp.kit.edu/~maggie/sHDECAY/`

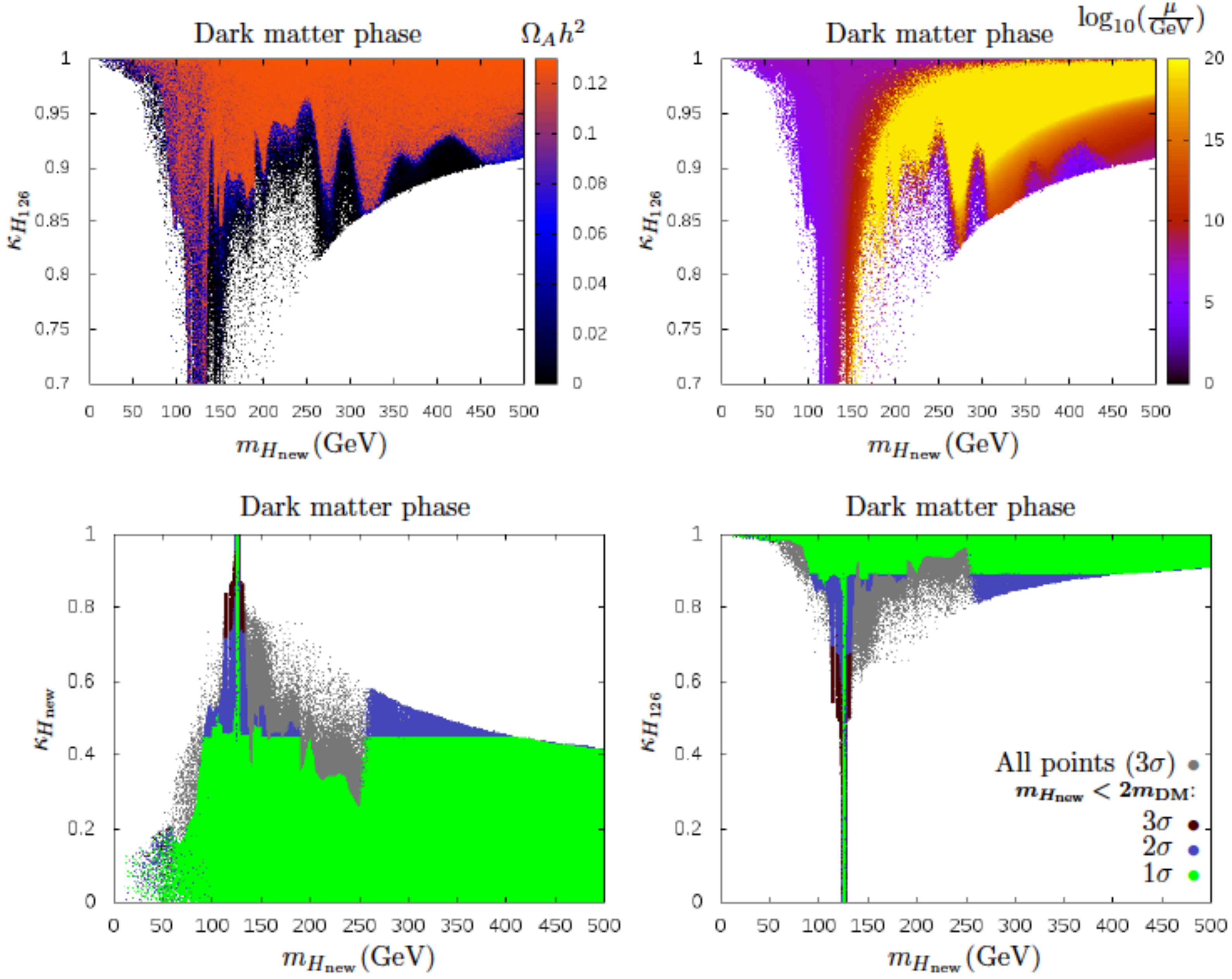
- EW corrections consistently off
- CxSM and also RxSM

⇒ **We also turned EW off for 13 TeV** $\sigma(gg \to h_i)$

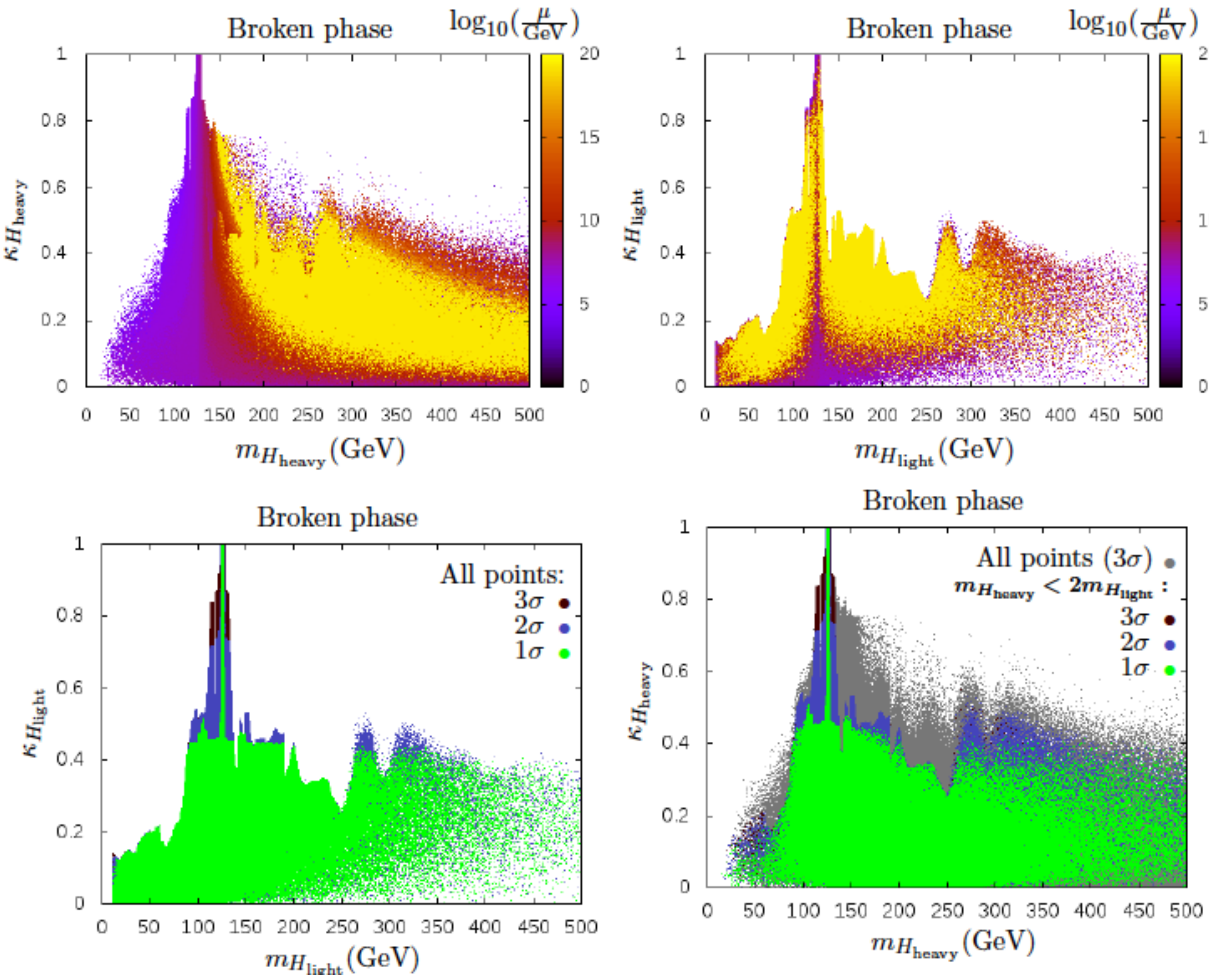
We define global signal rate for direct channels

$$\mu_i = R_{ih}^2 \sum_{X_{\rm SM}} {\rm BR}(h_i \to X_{\rm SM})$$

Theoretical motivation & LHC7+8 [arXiv:1411.4048]



Theoretical motivation + LHC7/8 [arXiv:1411.4048]



Constraints

- We take the lightest neutral scalar, h_1, to have a mass of 125 GeV in agreement with the latest results from ATLAS [28] and CMS [29].

- The accuracies in the measurements of the signal strengths in the processes $pp \to h_1 \to WW(ZZ)$, $pp \to h_1 \to \gamma\gamma$ and $pp \to h_1 \to \tau^+\tau^-$ are about 20% at 1σ [29, 30]. As shown in [9], imposing these run 1 constraints guarantees that the C2HDM automatically obeys all other run 1 constraints on the 125 GeV Higgs decays in this model. We will thus force μ_{VV}, $\mu_{\gamma\gamma}$ and $\mu_{\tau\tau}$ to be within 20% of the expected SM value

- The LHC results also allow us to put bounds on the heavier scalars h_2 and h_3. We impose the results on μ_{VV} [31] in the range $[145, 1000]$ GeV and on $\mu_{\tau\tau}$ [32] in the range $[100, 1000]$ GeV. We also use the results on $h_i \to ZZ \to 4l$ from [33] in the range $[124, 150]$ GeV and from [31] in the range $[150, 990]$ GeV, and on $h \to \gamma\gamma$ from [34, 35]. Finally we also impose the constraints stemming from the results based on the searches $h_i \to Zh_1 \to Zb\bar{b}(\tau^+\tau^-)$ [36] and $h_i \to Zh_1 \to llb\bar{b}$ [37].

- We consider the constraints on the charged Higgs Yukawa vertices that depend only on the charged Higgs mass and on $\tan\beta$. There is a new bound on $b \to s\gamma$, in Type II/F [38] of $m_{H^\pm} \geq 480$ GeV at 95% C.L.. Putting together all the constraints from B-physics [39, 40] and also from the $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ [41] measurement, we can state that roughly $\tan\beta \gtrsim 1$ for all models. LEP searches on $e^+e^- \to H^+H^-$ [42] and the LHC searches on $pp \to \bar{t}\,t(\to H^+\bar{b}$ [43, 44]) lead us to roughly consider $m_{H^\pm} \geq 100$ GeV in Type I/LS.

Constraints

- We consider the following theoretical constraints: the potential has to be bounded from below [45], perturbative unitarity is required [46–48] and all allowed points comply with the oblique radiative parameters [49–51].

- The scenarios we will present in the next section are a clear signal of CP-violation in models with an extended scalar sector. Models with a CP-violating scalar sector are constrained by bounds from electric dipole moments (EDMs) measurements. Although the search for the proposed final states should be performed from a model independent perspective, we will nevertheless estimate the most important constraints on the CP-violating phases in the context of the C2HDM [7, 52–56].

  The most stringent bound [7] comes from the ACME [57] results on the ThO molecule EDM. In order to have points with EDMs of an order of magnitude that conforms to the ACME result, we have computed the Barr-Zee diagrams with fermions in the loop. As we will see, the ACME bound can only be evaded by either going to the limit of the CP-conserving model or in scenarios where cancellations [55, 56] among the neutral scalars occur. These cancellations are due to orthogonality of the R matrix in the case of almost degenerate scalars [9]. We should finally point out that ref. [55] argues that the extraction of the electron EDM from the data is filled with uncertainties and an order of magnitude larger EDM than that claimed by ACME should be allowed for.

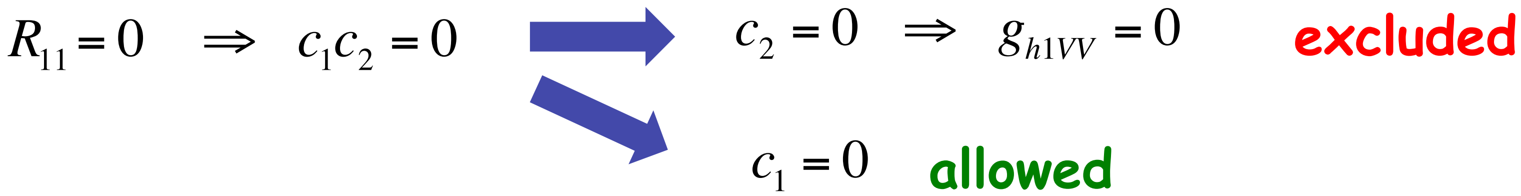
The zero scalar scenarios

- There is only one way to make the pseudoscalar component to vanish

$$R_{13} = 0 \quad \Rightarrow \quad s_2 = 0$$

and they all vanish (for all types and all fermions).

- There are two ways of making the scalar component to vanish



$$R_{11} = 0 \quad \Rightarrow \quad c_1 c_2 = 0$$

$$c_2 = 0 \quad \Rightarrow \quad g_{h1VV} = 0$$

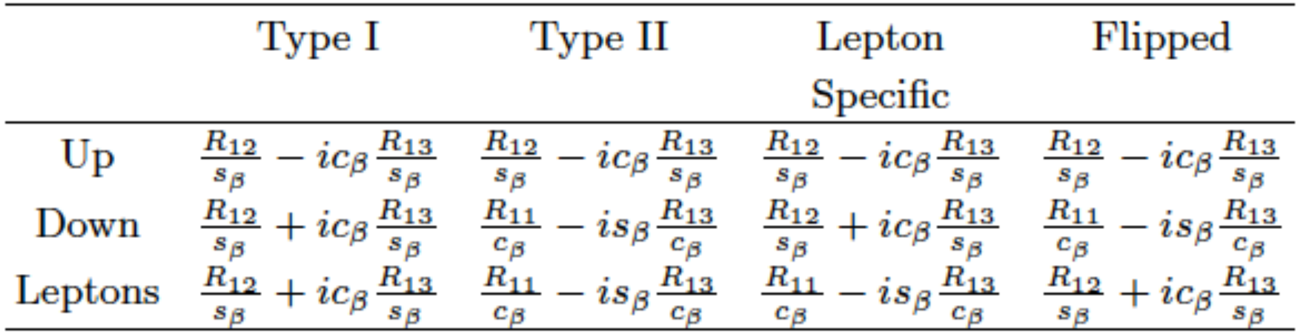
excluded

$$c_1 = 0$$

allowed

$$R_{12} = 0 \quad \Rightarrow \quad s_1 c_2 = 0$$

excluded



	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$